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STATE-OF-THE-ART SURVEY
OF METALLIC BELLOWS AND DIAPHRAGMS
FOR AEROSPACE APPLICATIONS

Dr. L. E. Hulbert, Dr. R. E. Keith, and T. M. Trainer
Battelle Memorial Institute
Columbus, Ohio

TECHNICAL REPORT NO. AFRPL-TR-65-215

November 1965

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November 30, 1965

Air Force Rocket Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
Edwards Air Force Base
California 93523

Attention Lt. John L. Feldman, RPRPD
Contract No. AF 04(611)-10532
AFSC Project No. 6753

Gentlemen:

Special Report--"State-of-the-Art Survey
of Metallic Bellows and Diaphragms for
Aerospace Applications"

Enclosed with this letter are five (5) copies and one (1) reproducible master copy of Technical Report No. AFRPL-TR-65-1 /5 This special report has been prepared as an initial part of a 2-1/2-year program on the "Development of Analytical Techniques for Bellows and Diaphragm Design".

On March 1, 1965, the Air Force Rocket Propulsion Laboratory, through contract with Battelle Memorial Institute, undertook a program to establish analytical design procedures, stress-analysis methods, techniques for manufacturing control, and other factors essential to the successful design and fabrication of metallic bellows and diaphragms. These objectives were to be accomplished by the following tasks:

1. The survey of knowledge available from the open literature and from industry on the design, analysis, fabrication, and testing of bellows and diaphragms

2. The identification of parameters pertinent to the design of bellows and diaphragms

3. The development of improved stress-analysis techniques and design procedures utilizing mathematical models and computer techniques

4. The investigation of improved fabrication, assembly, and testing techniques

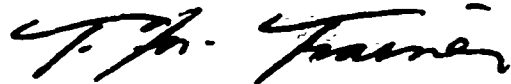5. The verification of selected analysis techniques and design procedures through laboratory evaluation

6. The classification of bellows and diaphragms

7. The publication of the program results in handbook format for distribution to selected facilities.

The enclosed special report has been prepared to summarize the results of the literature and industry survey for possible interested facilities. In addition, the report presents recommendations for activities during the remainder of the program which preclude the duplication of work formerly conducted, and which require priority to accomplish the objectives of the Air Force.

We have appreciated the opportunity to conduct the literature and industry survey and we look forward to the further achievement of the program objectives. Any comments on the research program and on this report will be appreciated.

Very truly yours,

T. M. Trainer, Director
Aerospace Components Division

TMT:mrm

STATE-OF-THE-ART SURVEY
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FOR AEROSPACE APPLICATIONS

Dr. L. E. Hulbert, Dr. R. E. Keith,
and T. M. Trainer.

FOREWORD

John L. Feldman
1/Lt., USAF
Project Engineer

ABSTRACT

A 2-1/2-year program has been undertaken to establish analytical design procedures, stress-analysis methods, techniques for manufacturing control, and other factors essential to the successful design and fabrication of metallic bellows and diaphragms. The initial phase of the program has included a state-of-the-art survey to assist in the determination of the best means of accomplishing the over-all program objectives. This report summarizes the results of the survey and presents recommendations for the remainder of the program. An annotated bibliography of 376 references is included.

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ABBREVIATIONS AND SYMBOLS

φ, θ	coordinates of a point on the middle surface
s	distance measured from an arbitrary origin along the meridian in the positive direction of φ
R_φ, R_θ	principal radii of curvature of the middle surface
r	$R_\theta \sin \varphi$
E	Young's modulus
ν	Poisson's ratio
h	thickness of shell
K	$Eh/(1 - \nu^2)$
D	$h^2 K/12$
w, u_φ, u_θ	components of displacement
$\beta_\varphi, \beta_\theta$	angle of rotation of normal
p_φ, p_θ, p	components of surface tractions
m_φ, m_θ	components of moment
$N_\varphi, N_\theta, N_{\theta\varphi}$	membrane stress resultants
$M_\varphi, M_\theta, M_{\theta\varphi}$	moment resultants
Q_φ, Q_θ	transverse shear resultants
N, Q	effective shear resultants
$(\ )_{,x}$	partial derivative with respect to x
$\epsilon_\theta, \epsilon_\varphi, \epsilon_{\theta\varphi}$	membrane strains
$\kappa_\theta, \kappa_\varphi, \kappa_{\theta\varphi}$	bending strains

INTRODUCTION

The Air Force Rocket Propulsion Laboratory has a primary responsibility of providing advanced technology for rocket propulsion systems through exploratory development programs. As a part of this mission, improvements in the performance and reliability of fluid-system components (valves and regulators) are being pursued vigorously. This is being accomplished by investigations into individual component parts or modules; i.e., seals, fittings, seats, poppets, and actuators.

The Air Force Rocket Propulsion Laboratory, through a contract with Battelle Memorial Institute, is establishing analytical design procedures, stress analysis methods, techniques for manufacturing control, and other factors essential to the successful design and fabrication of bellows and diaphragms. The final results of the program will be published in handbook format which will be distributed to selected facilities.

The initial phase of the program has involved a literature and industry survey to determine the present state of the art of bellows and diaphragms. This report summarizes the results of the survey and presents recommendations for activities during the remainder of the program which require priority to achieve the objectives of the Air Force.

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SUMMARY AND RECOMMENDATIONS

Approximately 50 manufacturers are engaged partially or entirely in the design and manufacture of metallic bellows and diaphragms for the aerospace industry. The availability of bellows is significantly different from that of diaphragms. Bellows are used in sufficiently large quantities that most manufacturers offer a range of sizes and materials. Although bellows for aerospace applications are rarely stock items, tooling is available for "standard" configurations and delivery can usually be made within a period of several weeks. Bellows are available as separate items and as special assemblies. Diaphragms, on the other hand, are not usually advertised for sale. While diaphragms can be obtained from certain firms on special order, most diaphragms are designed and fabricated "in-house" as parts of particular components.

Considerable theory has been developed concerning the behavior of bellows and diaphragms. However, the theory is complex and the performance of the actual items is affected by variations in material and fabrication parameters; consequently, bellows and diaphragms are designed almost entirely on the basis of empirical methods and experimental data developed by each company. Thus, while it is possible to predict the performance of bellows similar to those which have been manufactured and operated previously, it is difficult to predict the performance of new designs, or of old designs operating under new conditions.

Considering the wide variety of factors influencing the operation of aerospace bellows and diaphragms, the performance of these items is better than might be expected. However, it is believed that their performance will be significantly improved through the accomplishment of the major objectives of the program, i.e.:

1. The development of improved stress-analysis techniques and design procedures utilizing mathematical models and computer techniques

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2. The investigation of improved fabrication, assembly, and testing techniques

3. The verification of selected analysis techniques and design procedures through laboratory evaluation

4. The classification of bellows and diaphragms

5. The publication of the program results in handbook format for distribution to selected facilities

A large amount of work has been done on the design, fabrication, and evaluation of metallic bellows and diaphragms. The many configurations and performance characteristics considered, and the many design approaches utilized make the application of this information difficult. During the remainder of the program it is recommended that the emphasis be directed to experimentally determining the accuracy and range of validity of the most meaningful theories and synthesizing these theories into an easily used design procedure. Because of the intensive effort being devoted elsewhere to the study of the large plastic deformation of metallic bellows and diaphragms, it is recommended that the present program be concerned with metallic bellows and diaphragms operating largely in the elastic region. It is further recommended that the work on diaphragms be limited to corrugated diaphragms, because this type of diaphragm is usually used in aerospace components.

LITERATURE AND INDUSTRY SURVEY

The literature survey included a review of technical papers, text-books, articles, and government reports on bellows and diaphragm design, performance, and analysis. Selected material in related areas such as manufacturing, stress analysis, and testing was also reviewed. The industry survey included the solicitation of brochures from manufacturers, and trips to representative manufacturers and users of bellows and diaphragms to determine the design, fabrication, and evaluation procedures currently in use.

Literature Survey

An extensive bibliography of pertinent published material was prepared. Many of these references had been identified during the conduct of previous projects at Battelle. Additional references were located by a detailed search of Applied Mechanics Reviews, Chemical Abstracts, Instrument Abstracts, Applied Science and Technology Index, Nuclear Science Abstracts, and U. S. Government Research and Development Reports. Copies of most of the references were ordered. As the material was received, it was reviewed and abstracted, and copies of other pertinent articles were ordered. Approximately 500 published references were reviewed.

To locate additional government reports, machine searches were requested from the Defense Documentation Center and from the Scientific and Technical Information Division of NASA. It was requested that the DDC search include the years 1950 to the present, while the STID search was requested for the years 1961 to the present. (The file in the latter facility has only recently been automated.) A search was also made of the Transducer Information Center at Battelle, which is sponsored by the Air Force, and a bibliography of reports was requested from the Interservice Data Exchange Programs. The IDEP is a group of companies and government agencies that circulates brief reports on the test results of various aerospace components, to eliminate the duplication of costly testing. As a result of these inquiries, 61 references were ordered from the DDC, 24 from the STID, 18 from the TIC, and 21 from the IDEP.

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An annotated bibliography of the most pertinent references received during the literature survey is presented at the end of the report. An examination of this material will show a large amount of information of a theoretical nature. A significant amount of information pertains to design and experimental evaluation, but there is little information on fabrication. Although useful information may remain in as yet unlocated government reports, the references listed in this report constitute a reasonably comprehensive bibliography of the unclassified literature on metallic bellows and diaphragms.

Industry Survey

Initially, letters were sent to advertised manufacturers of bellows and diaphragms requesting design information and brochures. As the program progressed, additional firms were identified and trips were made to 21 representative manufacturers. Table 1 lists the manufacturers identified during the survey, and the types of bellows and diaphragms made by these firms.

Visits were also made to four representative users of bellows and diaphragms: (1) Atomics International, Division of North American Aviation, (2) Calmec Manufacturing, (3) The Missile and Space Division of Douglas Aircraft, and (4) Parker Aircraft. Atomics International has done considerable work for the AEC on the design and evaluation of bellows for high-temperature conditions where fatigue and creep are primary considerations. Calmec is primarily a manufacturer of valves, many of which use electroformed bellows with low spring rates and large deflections. Both the Santa Monica and Huntington Beach facilities of Douglas are utilizing bellows on the Saturn IV and other aerospace applications. Parker Aircraft uses bellows for a variety of pressure measurement and actuation applications.

TYPICAL BELLOWS AND DIAPHRAGMS

Bellows and diaphragms are thin elements whose deflection characteristics are utilized to provide movement in the structure of fluid systems. Usually these items are used when the need for motion is combined with the need

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TABLE 1. BELLOWS AND DIAPHRAGM MANUFACTURERS FOR THE AEROSPACE INDUSTRY

Manufacturer	Formed Bellows Max OD, inches	Formed Bellows Max Pres-sure, psi	Welded Bellows Max OD, inches	Welded Bellows Max Pres-sure, psi	Deposit. Bellows Max OD, inches	Deposit. Bellows Max Pres-sure, psi	Machined Bellows Max OD, inches	Machined Bellows Max Pres-sure, psi	Machined Diaphragms Max OD, inches	Machined Diaphragms Max Pres-sure, psi	Brass	Phosphor Bronze	Beryllium Copper	Stainless Steel	17-7 PH	AM 350	Aluminum	Nickel	Inconel X	Titanium	Other
Aero-Flex Corp., 7952 Othello, San Diego 11, California	42	10M												X	X	X	X		X	X	X
Aeroquip Corp./Marman Div, 11214 Exposition Blvd., Los Angeles, Cal	60	2400												X	X		X		X	X	
Alloy Bellows, Inc., 18123 Roseland Ave., Cleveland, Ohio	12	2500			2	500			2	300	X	X	X	X	X	X		X	X		X
*Anaconda Mtl Hose Div, Anaconda American Brass, Waterbury, Conn.	72	600															X	X	X	X	X
*Arrowhead Products, 4411 Katella Ave., Los Alamitos, California	39	6M												X	X	X	X	X	X	X	X
*Avica Corp., Box 180, Newport, Rhode Island	12	4M												X	X	X					
*Belfab Corp., P. O. Box 1381, Daytona Beach, Florida			20	6M					20				X	X	X	X			X	X	X
Bell-Metrics Corp., 12835 Arroyo St., San Fernando, California			24	2M										X	X	X		X	X	X	
*Borg-Warner Corp., P.O. Box 2017 Terminal Annex, Los Angeles, Cal.			12	10M										X	X	X		X	X	X	X
Caldwell Engine Labs, 8256 San Fernando Road, Sun Valley, Calif.	12	6M																			
Cartriseal Corp., 3515 W. Touhy Ave., Lincolnwood, Illinois			8	500										X	X	X			X	X	X
Circle Bellows Welding, 3021 N. San Fernando Road, Burbank, Calif.	20	10M	15	2M									X	X	X		X	X	X	X	
Chicago Rawhide Mfg. Co., 1301 Elston Ave., Chicago, Illinois									15	1M			X	X	X	X	X	X	X	X	X
Cliflex Bellows Corp., 45 West 3rd St., South Boston, Mass.	4	4M							**	**	X	X	X	X		X	X	X	X		
DK Mfg. Co., Aerospace Div, 100 N. Island Ave.; Batavia, Ill.	36	3M												X	X	X	X	X	X	X	X

(Machined Bellows columns annotated: no materials given)

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TABLE 1. (CONTINUED)

Manufacturer	Formed Bellows Max OD, inches	Formed Bellows Max Pres., psi	Welded Bellows Max OD, inches	Welded Bellows Max Pres., psi	Deposit. Bellows Max OD, inches	Deposit. Bellows Max Pres., psi	Machined Bellows Max OD, inches	Machined Bellows Max Pres., psi	Dia-phragms Max OD, inches	Dia-phragms Max Pres., psi	Brass	Phosphor Bronze	Beryllium Copper	Stainless Steel	17-7 PH	AM 350	Aluminum	Nickel	Inconel X	Titanium	Other
Electroforms, Inc., 231-39 East Gardena Blvd., Gardena, Calif.					**	500												X			X
*Precision Mtl Prod Div, Fairchild Camera, El Cajon, Calif.	48	10M												X	X	X			X	X	X
Flexible Metal Hose Mfg Co., W. 16th & Superior, Costa Mesa, Cal.	18	3M												X	X	X	X	X	X		X
Flexonics Div, Calumet & Eacle, Inc., 300 E. Devon, Bartlett, Ill	7.5	2500									X	X	X	X	X			X	X		X
Fulton Sylphon Div, Robertshaw Controls, Box 400, Knoxville, Tenn	**	**	**	**	10	5M					X	X	X	X	X	X	X	X	X	X	X
*Gardner Industries, 15180 Raymer, Van Nuys, California	14	10M																			X
Hyde, Div of Bath Iron Wks, Lakeside Office Pk, Wakefield, Mass.	72	300					32	25M						X	X	X	X	X	X		X
*Hydrodyne Div, Donaldson Co. Inc. 7350 Coldwater Canyon, N. Hollywd											X	X	X	X	X	X	X	X	X	X	X
*Metflex Mfg Div, U.S. Flex Metallic Tub., 454 E. 3rd, Los Angeles	48	**												X	X	X	X	X	X		X
Koller Products Company, 8 Littel Road, Hanover, N. J.			14	8M																	X
Kollsman Instrument Corp., 80-08 45th Ave., Elmhurst, N. Y.	5	vac	5	vac					5	vac	X	X	X	X	X	X	X	X		X	X
*Koppers Co., Bush and Hamberg Sts Baltimore, Maryland			20	**										X	X	X	X				X
Marquette Coppersmithing Co., P.O. Box 4584, Philadelphia, Pa.	**	**	**	25			132	**	**	50	X	X	X	X	X	X	X	X	X	X	X
Master Products Mfg. Co., 3481 E. 14th, Los Angeles, Calif.	36	12M	20	3M					20	3M	X	X	X	X	X	X	X	X	X	X	X
*Mechanicals Corp., 11447 Joanne Place, Culver City, California					12	**			3	1M								X			

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TABLE 1. (CONTINUED)

Manufacturer	Formed Bellows OD, inches	Formed Bellows Pres., psi	Welded Bellows OD, inches	Welded Bellows Pres., psi	Deposit. Bellows OD, inches	Deposit. Bellows Pres., psi	Machined Bellows OD, inches	Machined Bellows Pres., psi	Diaphragms OD, inches	Diaphragms Pres., psi	Brass	Phosphor Bronze	Beryllium Copper	Stainless Steel	17-7 PH	AM 350	Aluminum	Nickel	Inconel X	Titanium	Other
*Metal Bellows Corp., 1075 Providence Highway, Sharon, Mass.			18	**										X	X	X		X	X	X	X
Mini-Flex Corp., 4515 Manhattan Beach Blvd., Lawndale, Calif.	1.5	10M									X	X	X	X	X	X	X	X	X	X	X
National Bellows, Div of Van Allen-Andrews, Stratford, Conn.			2⅜	700										X							
Pacific Bellows, P. O. Box 1182 La Jolla, California	120	600												X							
Reliance Steel and Aluminum Co., 2537 E. 27th, Los Angeles, Calif.	**	**												X			X				X
Richmond Engineering Co., P. O. Box 765, Northridge, Calif.	36	10M	18	5M					8	50	X	X	X	X	X	X	X	X	X	X	X
*Robertshaw Controls Co. Milford Div, 155 Hill St., Milford, Conn.	4	3M	4	1500					2¼	**	X	X	X	X	X	X	X		X		X
*Sealol, Inc., 18210 Sherman Way, Reseda, California			**								X	X	X	X	X	X		X	X	X	X
*Servometer Corp., 82 Industrial East, Clifton, New Jersey					3	10M												X	X	X	X
*Solar Div., International Harvester, San Diego, California	36	15M					10	15M						X	X	X	X	X	X	X	X
*Stainless Steel Products, 2980 N. San Fernando Blvd, Burbank, Calif.	48	10M											X	X	X	X	X	X	X	X	X
Standard Bellows Co. 108 Elm St., Thompsonville, Conn.			12	5M					6	5M	X	X	X	X	X	X	X	X	X	X	X
*Standard-Thompson Corp., 152 Grove St., Waltham, Mass.	40	1500	6	1M			10	800			X	X	X	X	X	X	X		X	X	X
*Strasa Industries, 790 Greenfield Drive, El Cajon, California	14	4M										X	X	X	X	X	X		X	X	X

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TABLE 1. (CONTINUED)

Manufacturer	Formed Bellows		Welded Bellows		Deposit Bellows		Machined Bellows		Machined Diaphragms		Materials										
	Max OD, inches	Max Pres-sure, psi	Max OD, inches	Max Pres-sure, psi	Max OD, inches	Max Pres-sure, psi	Max OD, inches	Max Pres-sure, psi	Max OD, inches	Max Pres-sure, psi	Brass	Phosphor Bronze	Copper Beryllium	Stainless Steel	17-7 PH	AM 350	Aluminum	Nickel	Inconel X	Titanium	Other
Titeflex, Inc., 603 Hendee St. Springfield, Mass.	4.	1500	4	200							X		X	X	X	X			X	X	X
Tube Turns Div, Chemetron Corp. 624 E. Broadway, Louisville, Ky.	48	1200												X	X	X	X	X	X	X	
*Westport Development and Mfg. Co. 349 Boston Post Rd, Milford, Conn	4	4M	10	2M							X	X	X	X	X	X	X	X	X	X	
*Zallea Brothers, Inc., Taylor and Locust Sts., Wilmington, Delaware	240	10M										X		X	X	X	X	X	X	X	X

* Denotes companies visited by Battelle.
** Indicates no values given.

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for a hermetic seal. Bellows and diaphragms are made in many sizes and shapes from a variety of materials. This section of the report summarizes the principal types of metallic bellows and diaphragms that have been manufactured, and the major types of applications in which they have been used.

By mutual agreement with the Air Force, the program is concerned only with bellows and diaphragms which operate either totally within, or largely within the elastic state. Thus, the work which has been done to develop bellows and diaphragms as expulsion devices for fluid systems is not described in this report, although references on the subject are included in the bibliography.

Bellows Convolutions

Most metallic bellows are cylindrical elements which contain annular circumferential corrugations. In flexible hose, the corrugations may be formed in a continuous helix. Some bellows are not cylindrical but have elliptical or other noncircular cross sections. However, these shapes are sufficiently unusual that they are not included in the program.

Bellows are classified according to one of the four primary methods of manufacture, i.e., (1) formed, (2) welded, (3) deposited, or (4) machined. Within these classifications, the bellows are usually categorized according to the appearance of the convolution cross section, as shown in Table 2.

Formed Bellows

Formed bellows constitute approximately 75 percent of the bellows which are manufactured. They can be produced in a variety of materials and sizes at relatively low cost. Diameters up to four feet are readily available and one manufacturer advertises diameters up to 50 feet. Although Table 2 shows only single-ply configurations, most formed bellows can be made with multiple plies. Three- and four-ply bellows are common. Multiple plies are used to provide a lower spring rate than would be obtained with a single ply equal in thickness to the total thickness of the multiple plies.

Semitoroidal. Semitoroidal bellows are attractive for materials with relatively low ductility. The form also offers good pressure capability

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TABLE 2. MAJOR BELLOWS CONVOLUTIONS AND CHARACTERISTICS

	Convolution Shape	Axial Spring Rate	Long Stroke Capability	Resistance to Diff. Pressure
FORMED				
Semitoroidal		very high	very poor	very good
U-Shaped		medium	fair	fair
U-Shaped, Ext. Ring		high	fair	very good
U-Shaped, Int. Ring		high	fair	very good
U-Shaped, Ext. T. Ring		high	fair	very good
S-Shaped		medium	fair	fair
S-Shaped, Ext. Ring		high	fair	very good
Toroidal, Ext. Pressure		very high	poor	excellent
Toroidal, Int. Pressure		very high	poor	excellent
WELDED				
Flat		medium	fair	good
Stepped		low	good	fair
Single Sweep		medium	good	good
Nested Ripple		very low	excellent	poor
DEPOSITED				
U-Shaped (can be varied)		low	good	fair
MACHINED				
Rectangular		high	fair	excellent

and stability. The convolutions may be truly semicircular, elliptical, or some combination of curves. A low deflection capability per convolution and a high spring rate are major limitations of this configuration.

U-Shaped. When flat sections are placed between the semitoroidal sections, a U-shaped, or flat-plate-bellows configuration is formed. Over 50 percent of all the bellows are of this type. The shape is amenable to any of the methods for manufacturing formed bellows, a variety of performance characteristics can be achieved by varying the radii and depth of convolution, and supporting devices are easily installed externally or internally.

S-Shaped. The S-shaped bellows is similar to the U-shaped bellows. By slanting the straight sections between the semitoroidal sections, or by connecting the semitoroidal sections with curved sections, it is possible to form more convolutions and thus achieve more deflection per unit length. The S-shaped bellows is not as easy to manufacture, and is not as amenable to the use of supporting devices as the U-shaped bellows.

Toroidal. Toroidal bellows have been developed to reduce the pressure-induced stresses in the bellows. By using a shape which is essentially circular, the effects of pressure are more evenly distributed along the convolution. In addition, the stresses in the convolution are less affected by an increase in bellows diameter than is the case with the other convolution shapes. The Marquette Coppersmithing Company claims that their "OMEGA" shape distributes the stresses more evenly than a true toroidal bellows. Zallea Brothers advertise a "HyPTor", or modified toroidal shape which is satisfactory for intermediate pressures and is more flexible than a true toroidal shape. Although the toroidal bellows permit high operating pressures, it is more difficult to manufacture than the other formed bellows and has a high spring rate.

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Welded Bellows

Approximately 20 percent of the manufactured bellows have welded convolutions. Welded bellows are made up of shaped diaphragms which are alternately welded together at the inner and outer diameters. Although they are more expensive to manufacture than formed bellows, welded bellows offer three significant advantages over formed bellows: (1) a wider choice of materials, (2) more deflection per unit length, resulting in shorter assemblies or longer strokes, and (3) a wider choice of performance characteristics because of a greater variety of convolute dimensions and shapes. Although Sealol is offering a two-ply welded bellows, most welded bellows have a single ply.

Because the diameter of the welded bellows is determined by the diameter of the stamped diaphragm, welded-bellows sizes are limited by the available stamping equipment. In general, welded bellows are available in sizes from 1/2 inch to 7 inches outside diameter, but bellows in excess of 12 inches in diameter have been produced.

Table 2 summarizes the major types of welded convolutions, and their primary characteristics. Most welded bellows are of the nested-ripple configuration because this design makes maximum use of the advantages of low spring rate and compactness. However, the other configurations have attractive characteristics for certain applications.

Deposited Bellows

Two kinds of deposited bellows are commercially available: chemically deposited, and electrodeposited. Both methods can be used to produce any shape that can be deposited on a machined mandrel. In each method an aluminum mandrel is machined for each bellows, and after the bellows material is deposited, the mandrel is dissolved. The primary advantages of the processes are the ability to produce: (1) very thin-walled bellows, (2) nonwelded bellows, (3) very small bellows, and (4) some special shaped bellows.

Chemically deposited bellows are produced by Mechmetals Corporation from a material called "Mechmetal". Although the material is acknowledged to

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be about 95 percent nickel, its exact composition and the method by which it is deposited are proprietary. Chemically deposited bellows can be made with wall thicknesses from 0.0003 inch to 0.005 inch, and with diameters from 0.060 inch to 7.00 inches. Electrodeposited or electroplated bellows are usually produced in nickel or nickel-cobalt alloy. Sizes are available from 0.063 inch to 1.250 inches in diameter, with wall thicknesses varying from 0.0003 inch to 0.006 inch.

Machined Bellows

Machined bellows are turned or ground from bar stock, tubing, or forged rings of most materials used in other types of metallic bellows, as well as of materials not found in sheet stock. High-strength, high-endurance, heat-treatable tool steels, in addition to high-strength, low-modulus titanium alloys can be used. The design of machined bellows is customized, with most machined bellows having high spring rates. Machined bellows have been made from 1/4 inch to 60 inches in diameter, for pressures as high as 12,000 psi.

Bellows Assemblies

Although bellows can be used in an extremely wide variety of ways, certain types of assemblies have become relatively common. In general, these assemblies, some of which are shown in Figure 1, prevent certain types of motion and limit other types of motion.

Braided

Bellows with a length-to-diameter ratio greater than 1 may be distorted by internal pressure in a manner referred to as "squirm". When squirm occurs, the pressure may not be sufficient to distort the individual convolutions, but the bellows may deflect as a column, causing damage to one or more convolutions. Metal braiding is commonly used to provide external support for such bellows and to protect the bellows from external damage. This configuration is most common in flexible metal hoses. Braiding may cause abrasion of the bellows and it may accelerate corrosion of the bellows.

Braided Assembly	Sleeve Assembly
Slide Assembly	Internally Linked Assembly
Gimbal Assembly	Gimbal Assembly
Universal Assembly	Internal Gimbal-Universal Assembly
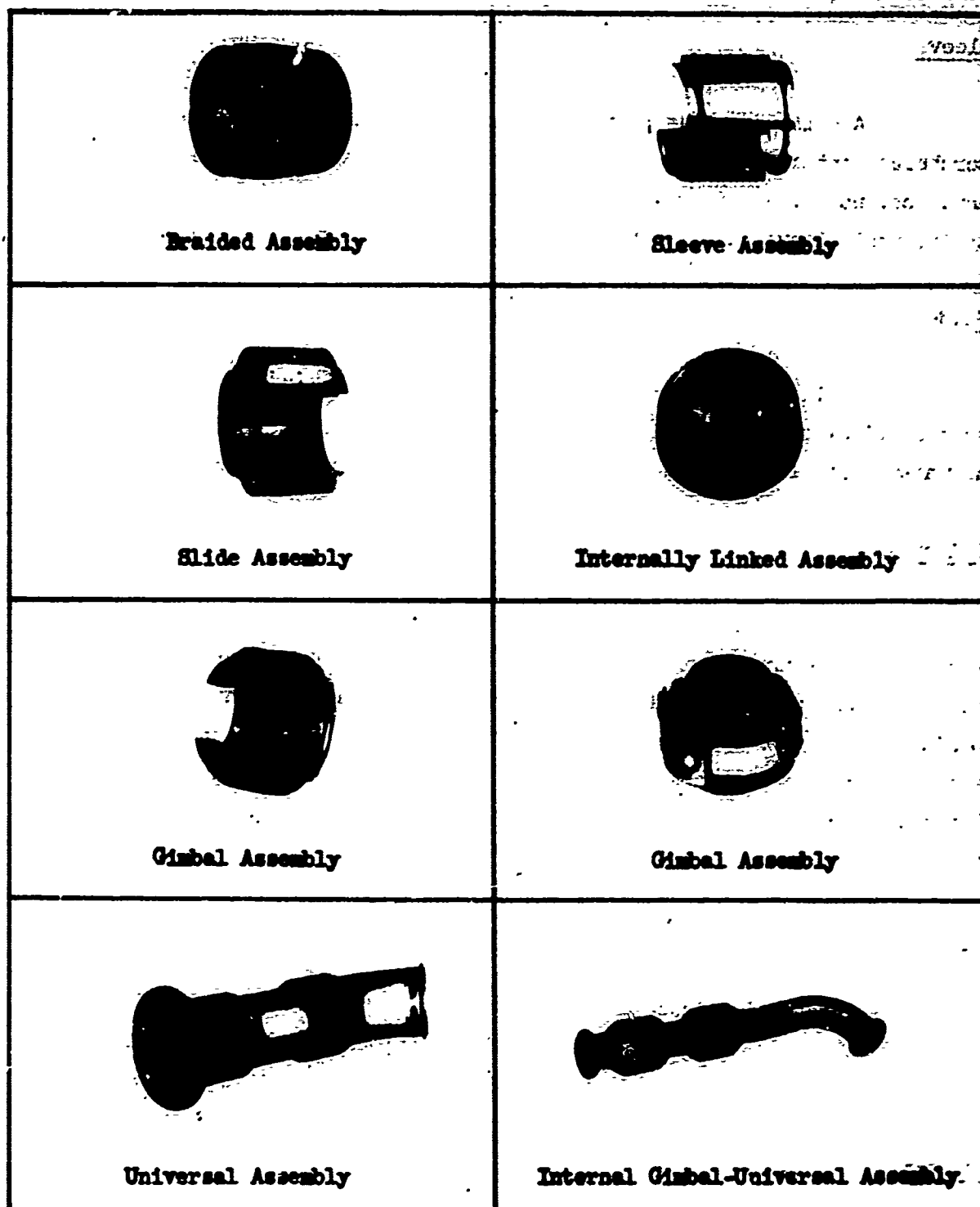
(Permission has been granted to use the above reproductions by the Aeroquip Corporation/Marman Division, Los Angeles, California)

FIGURE 1. TYPICAL BELLOWS ASSEMBLIES

Sleeve

A bellows may be provided with an internal sleeve to reduce fluid-scrubbing contact with the bellows. Such contact can cause flow losses, abrasion, noise, and flow-induced vibration which can lead to early failure. An internal sleeve can also be used to limit the amount of bellows compression.

Slide

A slide assembly is similar to a sleeve assembly except that tele-scoping sleeves provide axial guiding and prevent squirm. Slide assemblies are attractive for systems subjected to high surge pressures and temperatures.

Universal

A universal assembly contains two bellows joined by a common con-nector for the purpose of absorbing any combination of the three basic move-ments, i.e., axial deflection, lateral deflection, and angular deflection. Limit rods are often used to distribute the movement between the two bellows and to stabilize the common connector. This configuration can tolerate more lateral deflection or offset than one bellows equal in length to the two bellows.

Internally Linked

Internally linked assemblies utilize struts inside the bellows in the flow stream to limit movement in all directions. Such assemblies are simple, compact, and lightweight, but they introduce significant flow losses.

Hinged

A hinged bellows is designed to permit angular deflection in one plane only by the use of a pair of pins through hinge plates attached to the ends. The hinges and hinge pins must be designed to resist external forces and thrust due to internal pressure.

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Gimbaled

Gimbaled bellows assemblies provide for angular deflection in any direction from the tubing axis. Internal, or external gimbals can be used. They are made with two sets of hinge plates attached to a gimbal ring and function in a manner similar to a universal joint.

Pressure Balanced

A pressure-balanced bellows assembly is designed to absorb axial movement and/or lateral deflection while absorbing the end thrust by means of tie devices interconnecting the flow bellows with an opposed bellows also subjected to line pressure. This type of assembly is normally used where a change of direction occurs in a run of piping.

Bellows Applications

Bellows are used primarily in two ways: (1) as motion compensators, and (2) as calibrated transducers. Typical applications are discussed briefly.

Expansion Joints

Many bellows are used as expansion joints to compensate for movement occurring in pipe lines as a result of temperature changes and/or as a result of external loading. With the wide variety of piping systems, movement can be transmitted to a bellows as compression, extension, offset, rotation, or combinations of these motions. Most of the "standard" bellows assemblies have been developed to compensate for thermal changes in industrial tubing and piping systems.

Flexible Connectors

Bellows are often used to compensate for structural deflections, misalignment, and tolerance accumulation. These functions may be fulfilled by a short, plain bellows, or by relatively long, flexible metal hoses with metal braiding or other types of exterior covering.

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Pressure and Temperature Sensors

One of the most common uses for bellows is the actuation of some device as a function of a change in the pressure or temperature of a fluid system. The fluid may be external or internal to the bellows. For temperature sensing, the bellows system often incorporates a liquid whose vapor pressure reflects the temperature being sensed. The vapor pressure is then used to actuate the bellows. When the bellows moves in response to pressure changes, the movement is utilized to actuate a device such as a valve or switch. Because the bellows responds very quickly to changes, the movement can be used as a proportioning signal as well as an on-off signal. Diaphragms and Bourdon tubes are also used extensively for these functions.

Shaft and End-Face Seals

Although most reciprocating shafts are sealed with some type of packing, increasing requirements for reliable, hermetic sealing have resulted in the wider use of bellows for this purpose. The ability of a bellows to provide sealing and to act as a spring and motion compensator makes it ideal as a means of pressing face seals together on rotating shafts. Because of their compact construction and low spring rate, welded bellows are commonly used in face-seal assemblies.

Hydraulic Motors and Actuators

For small power requirements, particularly for remote operation, bellows can be used for converting mechanical work to hydraulic work or for converting hydraulic work to mechanical work. For example a liquid-filled system may consist of two bellows connected by tubing. The movement of one bellows causes movement of the other bellows.

Vibration Dampeners

Just as springs with frictional elements for energy adsorption are used as vibration dampeners in mechanical systems, bellows are used as

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vibration dampeners for fluid-containing structures. Because the bellows itself responds to certain vibration frequencies, care must be taken to assure that the bellows is not excited by the frequencies transmitted from the system structure.

Accumulators and Shock Absorbers

In a hydraulic system, a bellows can function as a flexible container to maintain oil flow or to absorb surge pressures. The primary requirements are long stroke, resistance to high differential pressure, and quick response.

Volume Compensators

For liquid systems of small volume, bellows furnish an attractive means of compensating for fluid expansion or contraction. Hermetically sealed floated instruments such as gyros and accelerometers are typical applications.

Flexible Couplings

Although bellows are not usually designed to transmit torsional loads, bellows have been found to be attractive for transmitting small torques, particularly for instrumentation-type equipment. The bellows can tolerate some misalignment and the torsional stiffness of the bellows insures accurate rotational transmission. Bellows-type flexible couplings are available for shafts up to 1/2 inch diameter.

Diaphragm Configurations

A diaphragm is a thin disk-like element which deflects in a direction substantially perpendicular to its flexible surface. Metallic diaphragms are classified as flat or nearly flat, and corrugated. They are used primarily as actuators to transform pressure into linear motion and force. Corrugated diaphragms are preferred for aerospace components such as valves and regulators because their average sensitivity over a large range of pressure is greater than flat diaphragms of the same size, their zero-position under no-load is more

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stable, much larger deflections can be obtained without permanent deformation, and a variety of pressure-deflection characteristics may be obtained for a given size diaphragm by using different depths or shapes of corrugations. This report is concerned only with corrugated diaphragms.

In contrast with the variety of information on bellows sizes and shapes contained in the open literature and listed in catalogs, little information has been obtained on commercially available corrugated diaphragms. The most complete discussion of possible diaphragm configurations and their performance characteristics is contained in a publication by Newell[1]* which has been approved by the Diaphragm Research Subcommittee of the American Society of Mechanical Engineers.

In general, the work reported by Newell[1] and by Wildhack, et al.[2] shows that the effect of increasing the number of corrugations is to increase the initial flexibility as well as the average flexibility over the usable range, although diaphragms with more corrugations may be more nonlinear. Diaphragms with shallower corrugations exhibit better initial flexibilities within limits but at the expense of decreasing the linear range. According to Wildhack, et al.[2] diaphragms made with triangular and trapezoidal shapes provide linear force-deflection characteristics for deflections up to at least 2 percent of the diameter with the trapezoidal shape being slightly stiffer and the triangular shape being slightly more flexible than the corresponding diaphragm with the same number of circular corrugations. Although empirical relationships have been developed, the design of corrugated diaphragms is reported to be largely a process of trial and error.

According to a survey by Giannini Controls,[3] corrugated diaphragms are manufactured in sizes from 0.875 to 6.0 inches in diameter, and are usually joined together in pairs to form a capsule. They can be used to sense pressures from 0.5 to 400 psi; however, the majority of units are used to sense pressures from 5 to 100 psi, and most units are less than 2.5 inches in diameter. Most diaphragms will not be more than 1 percent nonlinear if the displacement is kept below 2 percent of the diameter. If nonlinearity of more than 1 percent is acceptable, displacements up to 5 or 6 percent can be obtained.

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*References are given on page 67.

Diaphragm Applications

The publication by Newell[1] lists 15 major and several minor application classifications for corrugated diaphragms. The most important applications from the standpoint of this program are: (1) pressure and temperature sensors, (2) linear shaft seals, and (3) volume compensators. Since these applications have been discussed previously for bellows, they will not be repeated here. It should be noted that the primary advantages of diaphragms as compared with bellows are greater sensitivity and more compact shape for some components. Low deflection and low pressure capability are the primary limitations of diaphragms, although the pressure capability is often altered by the use of springs.

THEORETICAL ANALYSIS OF ELASTIC DEFORMATIONS OF BELLOWS AND DIAPHRAGMS

The theoretical investigation of the performance of bellows and diaphragms has had a long and sometimes colorful history. The main theoretical developments have taken place in the last half century since the deriva-tion of the H. Reissner-Meissner equations for the linear elastic deformations of the shell of revolution. Prior to the development of computers, the investigations were limited to attempts to derive approximate formulas for the stresses and deflections in axisymmetric shells of special shapes. However, the development of digital computers and the accompanying development of numerical methods has made it possible to obtain direct numerical solutions for the deflections and stresses in axisymmetric shells of arbitrary meridional shape.

This report section gives a brief description of approaches that have been used for developing solutions to the elastic deformation of bellows and diaphragms. The approaches may be divided into three major categories: (1) analytic, (2) finite-difference, and (3) direct-integration. The direct-integration approach will be discussed in some detail, since it is believed to be the most useful.

The Analytic Approach

The analytic solution for a general shell of revolution having an arbitrary meridional profile has not yet been found. However, approximate solutions have been derived for certain shells having constant meridional curvature. These include conical, toroidal, spherical, and cylindrical shells. Most bellows and diaphragms can be considered to be made up of a number of segments of shells of this type, and it is possible to synthesize solutions to these bellows and diaphragms by appropriately combining the solutions for their segments. An attempt to calculate the stresses in bellows and diaphragms in this way will be called the analytic approach.

As noted above, the theoretical analysis of shells of constant curvature has been studied intensively for the last half century. The bibliography lists some of the papers that have been written in this area. The number of papers bearing on the theory of axisymmetric shells is so great

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that only a selected list could be incorporated. However, except for the toroidal bellows, only a small number of bellows or diaphragm problems have been solved by combining the various analytic solutions.

An early application of this technique to the calculation of the stresses in a diaphragm was reported in a paper by Grover and Bell.[4] This solution required the inversion of a 40 x 40 matrix on a desk calculator! Of course, present-day applications of this technique use a computer to solve the matrix equations. A well-known application of this technique to the bellows problem is given in the paper by Laupa and Weil.[5] Also, in a recent study[6,7,8,9] Atomics International Division of North American Aviation, Inc. developed a computer program that used the analytic approach for analyzing single-ply toroidal and convoluted bellows with and without reinforcing rings and single-sweep welded bellows.

The chief disadvantage of this approach is that it is limited to bellows or diaphragm configurations that can be made up of sections that can be solved analytically. Each section, in addition to having constant meridional curvature, must also have constant thickness and must be isotropic and homogeneous. These parameters can be allowed to vary from segment to segment to account for the nonuniform thickness or variation in the elastic properties of the bellows. However, unless the bellows is broken into a fairly large number of segments, this may not be a satisfactory way to approximate shells with varying thickness or elastic properties.

Finally, all of the attempts to obtain relatively simple approximate formulas for bellows problems by making further simplifying assumptions are analytical approaches. The paper by Turner and Ford[10] gives one example of such an approximate solution. Many others are included in the bibliography.

The Finite-Difference Approach

The finite-difference approach involves choosing a set of grid points along the bellows and approximating the differential equation by finite-difference equations defined at the grid points. This approach has been used as the basis for a number of computer solutions for problems involving shells of revolution.[11,12,13,14]

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This technique is quite general and may be applied to the solution of arbitrarily shaped thin shells of revolution with varying thickness and elastic parameters*. Considerable progress has been made in solving the large matrices of the type that are encountered in this technique. These matrices are quasidiagonal and can be solved by successive elimination and back substitution technique. As a result, bellows problems can be solved by finite-difference codes such as the AVCO code[12] or the CEGB code[11] in a matter of one or two minutes on computer machines of the IBM 7090 class.[15]

Finite difference programs have been written with the capability of analyzing a variety of bellows configurations and loading conditions. For example, the AVCO code permits the analysis of bellows with both axisymmetric and nonsymmetric loading in the linear elastic range. It also permits the analysis of multi-layer shells in which the layers are completely bonded together along the entire length of the shell. The code developed at Bell Aerosystems Company[16] permits the analysis of the linear and nonlinear axisymmetric elastic deformation of bellows and the computer code recently developed at MIT[17] permits the analysis of axisymmetric plastic deformations of shells as well as the elastic deformation.

The chief disadvantage of the finite-difference techniques is that the accuracy of the solution depends on the choice of the mesh point spacing. Since this dependence is not known beforehand for a given problem, the user will either have to choose a mesh spacing finer than necessary or risk having to run the problem over again if his original choice of mesh spacing is not fine enough. This dilemma is even more serious when an iterative solution must be obtained for nonlinear problems. The direct-integration approach provides a way of overcoming this difficulty.

The Direct-Integration Approach

A number of direct numerical integration schemes have been developed for ordinary differential equations. Since most problems involving axisymmetric shells can be reduced to one-dimensional problems involving ordinary differential equations, numerical integration techniques can be used to solve them.

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* The capability of taking varying thickness and elastic parameters into account includes accounting for discontinuous changes in these quantities. This permits analysis of end fittings, weld beads, etc.

This fact has been long recognized. The problems mentioned above that have been solved by finite-difference techniques may also be solved by direct-integration techniques. One of the first computer solutions to a convoluted diaphragm problem[18] employed the Runge-Kutta integration approach. Subsequent to this work, a number of computer solutions were obtained with the Runge-Kutta technique.[19] However, it soon became apparent that the direct-integration techniques became inaccurate if applied to some shell problems. This phenomenon is discussed in the paper by Septowski, et al.[14] Briefly, the difficulty stems from the fact that self-equilibrating boundary loads on shells give rise to stresses only in a narrow "edge-effect" zone near the boundary. In solving a shell problem, it is necessary to take into account the boundary loads at both ends of the shell. However, the direct-integration approach integrates from one end of the shell to the other. As the effects of the boundary loads begin to decay, the numerical integration procedure begins to encounter truncation errors. If the shell is long enough, the truncation errors completely obliterate the desired answers. This effect might not be serious if the integration is carried out over only a half-convolution of most bellows. However, an integration over a full convolution would probably be inaccurate.

As a result of this deficiency in the direct-integration technique, many investigators turned to the finite-difference technique discussed above. An indication of this was that more of the general computer programs discovered in the literature search were based on the finite-difference than the direct-integration approach.

An ingenious way to extend the range of applicability of the direct-integration technique to include long shells has been developed by Dr. A. Kalnins.[20] A similar technique apparently was derived independently by Goldberg and Bogdanoff,[21] by Mirabal and Dight[22] and by Cohen.[23]

The essence of this technique is that the shell is first broken up into relatively short segments. The solutions for these segments are obtained by the direct-integration technique. Then these solutions are combined in such a way that the continuity equations between segments and the boundary conditions at the ends of the shell are satisfied simultaneously. This approach is similar to some of the analytic approaches that have been used. The principal difference is that the solution for each segment is determined by numerical integration rather than by analytical formulas.

It was mentioned earlier that direct integration could be used to solve the same bellows problems that have been considered using the finite-difference technique. For example, the Yale code[20] permits the analysis of the symmetric and nonsymmetric deformation of isotropic or orthotropic single- or multi-layer shells of revolution. (Here, as in the AVCO code, a multi-layer shell is considered to have layers completely bonded together along the entire length of the shell.) Arbitrary variations in thickness and elastic properties, including discontinuous variation, are easily accounted for. Thus, the effects of end fittings and weldments may be considered. Cohen[23] has also developed a computer program that permits the linear elastic analysis of orthotropic shells subject to either symmetric or nonsymmetric loads. Recently, the Yale code was extended to permit the analysis of the nonlinear axisymmetric elastic deformation of bellows.[24] As yet, there does not appear to be any program that utilizes the direct-integration approach to solve for the plastic deformation of bellows. However, this problem appears to be amenable to the direct-integration approach.

Thus, it appears that the multisegment direct-integration approach is fully as general as the finite-difference approach for shells of revolution. The big advantage of the direct-integration approach over the finite-difference approach is that the integration step size is automatically selected by the computer to give a uniform desired accuracy at all parts of the bellows. This means that the designer need not worry about choosing the mesh size as in the finite-difference approach. Further, with the direct-integration approach, he has control over the accuracy of the answers in contrast to the analytic approaches where the accuracy depends on the accuracy of the approximations made in deriving the analytic solution.

The multisegment variation of the direct-integration approach seems to have eliminated the major disadvantage of this approach. It appears to be applicable to all problems involving thin shells of revolution and should become the standard way of approaching these problems.

Derivation of Linear Thin-Shell Equations

The remainder of this section will be devoted to outlining the derivation of the linear thin-shell equations in a form useful for application of the numerical-integration techniques. The multisegment approach

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and some features of the integration techniques will then be discussed. For simplicity of presentation, only the case of axisymmetric deformation of shells of revolution will be discussed. The application of the numerical methods is practically the same for the case of axisymmetric or nonaxisymmetric loads, and it is believed that the procedure will be better understood if the equations are kept simple. The more general equations for nonsymmetric loads are derived in Kalnins' paper. Cohen's paper gives equations for orthotropic shells.

The underlying shell-theory assumptions that will be used for deriving the basic equations (in addition to the relative thinness of the shell) are: (1) that normals to the shell's middle surface deform into normals to the deformed middle surface without extension (this implies that transverse shear and normal strains are negligible), (2) that the transverse normal stress is negligible, and (3) that the components of the displacement u_φ and w and the rotation β_φ are sufficiently small to neglect second-order terms while the middle surface strains, ϵ_φ and ϵ_θ, are negligible. These assumptions form the basis for the classical linear thin-shell equations of H. Reissner-Meissner and Novozhilov*.

However, in order to use the direct-integration approaches, it is more convenient to express the shell-theory equations in terms of linear first-order equations in the quantities that appear in the natural boundary conditions along a rotational symmetric edge of the shell. For symmetric deformations, these parameters are (see Figure 2) the meridional membrane and bending stress resultants N_φ and M_φ, the transverse stress resultant Q_φ, the meridional displacement u_φ, the transverse displacement w, and the rotation β_p.

The derivation of the shell equations begins with the statement of the equilibrium equations, stress-strain relations, and strain-displacement equations. These equations have become quite standardized, at least for small axisymmetric deformations. The equations will be stated in the form given by Kalnins[20] and may be obtained from his Equations (6) through (13) by eliminating derivatives with respect to θ and eliminating terms that include $M_{\theta\varphi}$, $N_{\theta\varphi}$, p_θ, Q_θ, and m_θ. (These quantities are zero for axisymmetric deformations.)

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* An elegant derivation showing the relationship between these equations was presented recently by R. A. Clark[25].
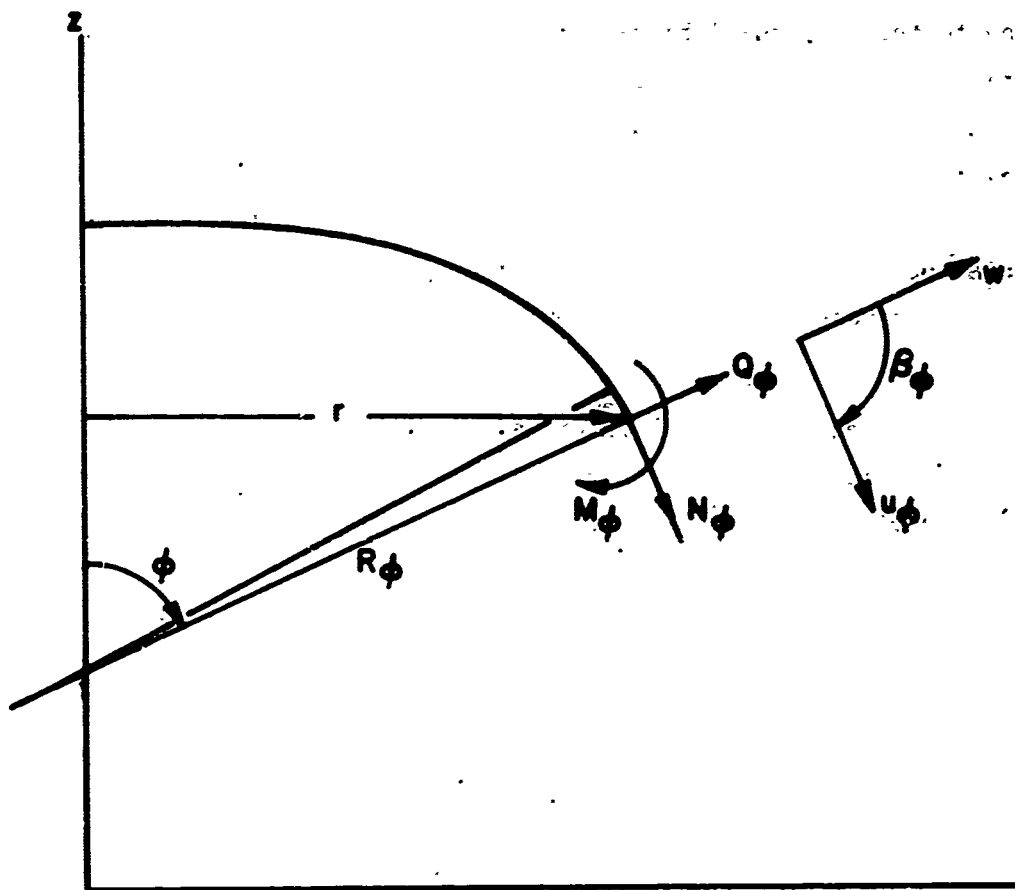
FIGURE 2.   AXIAL SECTION OF SHELL'S MIDDLE SURFACE
INDICATING STRESS RESULTANTS ACTING IN
THE rz-PLANE

The equations of equilibrium for axisymmetric deformations are:

$$(1) \quad \frac{r}{R_\varphi} N_{\varphi,\varphi} + (N_\varphi - N_\theta) \cos \varphi + \frac{r}{R_\varphi} Q_\varphi + r p_\varphi = 0.$$

$$(2) \quad \frac{r}{R_\varphi} Q_{\varphi,\varphi} + Q_\varphi \cos \varphi - N_\theta \sin \varphi - \frac{r}{R_\varphi} N_\varphi + r p = 0.$$

$$(3) \quad \frac{r}{R_\varphi} M_{\varphi,\varphi} + (M_\varphi - M_\theta) \cos \varphi - r Q_\varphi + r m_\varphi = 0.$$

The lengths r and R_φ are shown in Figure 2. The subscript φ after the comma denotes the derivative with respect to φ: $N_{\varphi,\varphi} = \frac{dN_\varphi}{d\varphi}$. N_θ and M_θ are the circumferential membrane and bending stress resultants; p and p_φ are components of the mechanical surface loads in the normal and meridional directions, and m_φ is the component of the moment of the surface loads.

The stress-strain relations are given by:

$$(4) \quad N_\theta = K (\epsilon_\theta + \nu \epsilon_\varphi)$$

$$(5) \quad N_\varphi = K (\epsilon_\varphi + \nu \epsilon_\theta)$$

$$(6) \quad M_\theta = D (\varkappa_\theta + \nu \varkappa_\varphi)$$

$$(7) \quad M_\varphi = D (\varkappa_\varphi + \nu \varkappa_\theta)$$

Where $K = Eh/(1 - \nu^2)$, $D = h^2 K/12$, E is Young's modulus, ν is Poisson's ratio, h is the shell thickness, ϵ_φ and ϵ_θ are the meridional and circumferential strains, and $\varkappa_\varphi$ and $\varkappa_\theta$ are changes in principal curvatures in the meridional and circumferential directions because of bending.

The strain-displacement relations are written as:

$$(8) \quad \epsilon_\theta = \frac{1}{r} (u_\varphi \cos \varphi + w \sin \varphi)$$

$$(9) \quad \epsilon_\varphi = \frac{1}{R_\varphi} (u_{\varphi,\varphi} + w)$$

$$(10) \quad \beta_\varphi = \frac{1}{R_\varphi} (-w_{,\varphi} + u_\varphi)$$

$$(11) \quad \varkappa_\varphi = \beta_{\varphi,\varphi} / R_\varphi$$

$$(12) \quad \varkappa_\theta = \beta_\varphi \cos \varphi / r .$$

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In order to apply the numerical integration approach, these 12 equations must be reduced to six equations in M_φ, N_φ, Q_φ, u_φ, w, and β. Further, it is more convenient to integrate along the arc-length, s, of the shell. This requires that the independent variable be taken as s rather than φ. This is a simple transformation, since:

$$(13)\quad \frac{d}{d\varphi} = R_\varphi \frac{d}{ds} \ .$$

As a first step in eliminating the unwanted variables, the quantities N_θ and M_θ are expressed in terms of the fundamental variables. Substituting (5) and (9) in (4) gives:

$$(14)\quad N_\theta = \nu N_\varphi + (1 - \nu^2)\, K\varepsilon_\theta$$
$$= \nu N_\varphi + (1 - \nu^2)\, \frac{K}{r}\, (u_\varphi \cos\varphi + w \sin\varphi) \ .$$

Substituting (7) and (12) in (6) gives:

$$(15)\quad M_\theta = \nu M_\varphi + (1 - \nu^2)\, D\varkappa_\theta$$
$$= \nu M_\varphi + (1 - \nu^2)\, \frac{D}{r}\, \beta_\varphi \cos\varphi \ .$$

Substituting (14) and (15) in Equations (1) through (3) gives the following equations:

$$(16)\quad \frac{r}{R_\varphi} N_{\varphi,\varphi} + \cos\varphi\, \{(1 - \nu)\, N_\varphi - (1 - \nu^2)\, \frac{K}{r}\, (u_\varphi \cos\varphi + w \sin\varphi)\}$$
$$+ \frac{r}{R_\varphi} Q_\varphi + r p_\varphi = 0 \ .$$

$$(17)\quad \frac{r}{R_\varphi} Q_{\varphi,\varphi} + Q_\varphi \cos\varphi - \nu M_\varphi \sin\varphi - \frac{r}{R_\varphi} N_\varphi + rp$$
$$- \frac{(1 - \nu^2)\, K \sin\varphi}{r}\, (u_\varphi \cos\varphi + w \sin\varphi) = 0 \ .$$

$$(18)\quad \frac{r}{R_\varphi} M_{\varphi,\varphi} + \{(1 - \nu)\, M_\varphi - (1 - \nu^2)\, \frac{D}{r}\, \beta_\varphi \cos\varphi\} \cos\varphi - rQ_\varphi + rm_\varphi = 0 \ .$$

Note that only the first term in each of these equations contains derivatives with respect to φ. Using the relation (13) and doing some minor rearranging gives:

$$(19) \quad N_{\varphi,s} = \frac{-(1 - \nu)\cos\varphi}{r} N_\varphi + (1 - \nu^2)\frac{K\cos\varphi}{r^2}(u_\varphi \cos\varphi + w \sin\varphi)$$

$$- \frac{Q_\varphi}{R_\varphi} - P_\varphi .$$

$$(20) \quad Q_{\varphi,s} = \frac{-Q_\varphi}{r}\cos\varphi + (\frac{1}{R_\varphi} + \frac{\nu}{r}\sin\varphi) N_\varphi +$$

$$\frac{(1 - \nu^2) K \sin\varphi}{r^2}(u_\varphi \cos\varphi + w \sin\varphi) - p .$$

$$(21) \quad M_{\varphi,s} = \frac{-\cos\varphi}{r}\{(1 - \nu) M_\varphi - (1 - \nu^2)\frac{D}{r}\beta_\varphi \cos\varphi\} + Q_\varphi - m_\varphi .$$

These are three of the equations that are needed. Three other equations of a similar type are needed for the derivatives of the displacements. Solving Equation (1) for $w_{,\varphi}$:

$$w_{,\varphi} = u_\varphi - \beta_\varphi R_\varphi, \text{ or}$$

$$(22) \quad w_{,s} = \frac{1}{R_\varphi} u_\varphi - \beta_\varphi .$$

Substituting Equations (8) and (9) in (5), and solving for $u_{\varphi,\varphi}$ yields:

$$\frac{u_{\varphi,\varphi}}{R_\varphi} = \frac{N_\varphi}{K} - \frac{w}{R_\varphi} - \frac{\nu}{r}(u_\varphi \cos\varphi + w \sin\varphi),$$

or from (13):

$$(23) \quad u_{\varphi,s} = \frac{N_\varphi}{K} - w(\frac{1}{R_\varphi} + \frac{\nu}{r}\sin\varphi) - \frac{\nu u_\varphi}{r}\cos\varphi .$$

The expression for $\beta_{\varphi,s}$ is derived by substituting Equations (11) and (12) in Equation (7) and solving for $\beta_{\varphi,\varphi}$ to give:

$$\frac{\beta_{\varphi,\varphi}}{R_\varphi} = \frac{M_\varphi}{D} - \frac{\nu \beta_\varphi \cos\varphi}{r} \text{ so that:}$$

$$(24) \quad \beta_{\varphi,s} = \frac{M_\varphi}{D} - \frac{\nu \, \beta_\varphi \cos \varphi}{r} \, .$$

Equations (19) through (24) are the desired first-order equations for the fundamental variables. Once these quantities are found, the other variables such as N_θ and M_θ may be easily found. (The requisite formulas for N_θ and M_θ are Equations (14) and (15)).

It may be noted that no approximations were made in deriving the Equations (19) through (24) from Equations (1) through (12). Of course, the original equations incorporate the "thin-shell" approximations noted at the beginning of the derivation.

Equations (19) through (24) are solvable by numerical integration techniques. Such techniques are applicable to the solution of initial value problems in which all of the information about the solution is known at an initial point and the values of the solution at the remaining points of the interval are determined by integrating the differential equations. (Actually the shell problem requires a modification in the technique since only three conditions are given at each edge of the shell.) It shall be shown presently how this is handled. The techniques can be illustrated by considering a first-order differential equation:

$$(25) \quad y' = f(x, y) \quad a \leq x \leq b, \text{ where } y' = dy/dx \, .$$

Let the initial value of y at $x = a$ be called y_0. It is assumed that y_0 and $f(a, y_0)$ are known and that it is desired to calculate $y(x)$, $a \leq x \leq b$. The numerical techniques consist of procedures to integrate Equation (25) stepwise in small increments of x. The first step consists of calculating $f(x_1, y_1)$ where $x_1 = a + \delta x$, and δx is some small interval. The integration is complicated by the fact that y_1 is not known. It must be determined simultaneously with $f(x_1 \, y_1)$.

Two major types of integration schemes used for one-dimensional initial-value problems are the Runge-Kutta type procedures and the predictor-corrector type procedures. The Runge-Kutta procedures are equivalent to expanding $f(x, y)$ in Taylor's series about the initial point (a, y_0) and evaluating y_1' and y_1 approximately by a truncated Taylor's series (usually of fourth order). The derivatives of $f(x, y)$ are evaluated at (a, y_0). A number of variants of the Runge-Kutta process exist depending on the formulation of the approximate Taylor's series.

The predictor-corrector schemes differ from the Runge-Kutta process
in that after the approximate values of y_1 and y_1' are found or "predicted"
at x_1, new values of y_1 and y_1' are found by "correcting" the values found in
the prediction step. In most of the predictor-corrector methods, the corrector
can be applied iteratively (each time with the newest value of y_1) until the
exact value of y_1 is determined. The chief deficiency of the predictor-
corrector schemes is that as many as four successive values of solution are
needed as input to the difference formulas. In order to start the integration
by this scheme, it is usually necessary to calculate these several values by
some other method such as the Runge-Kutta method.

The accuracy of any of the numerical-integration schemes depends
on the spacing, δx, at each step of the iteration. This accuracy may be
determined with error formulas in some cases or by integrating at each point
over two values of δx and comparing the results. Using one or the other
estimate of the accuracy of each integration step, it is then possible to
automatically adjust the step length to obtain the desired accuracy in the
integration. A number of integration codes have been written with this facility.
Detailed discussions of these integration techniques are contained in a number
of books on numerical analysis such as Fox.[26] Many of these books discuss
the integration of systems of equations of the type (19) - (24).

It was mentioned earlier that the shell problem requires specifi-
cation of boundary conditions on both ends of the shell. The direct integra-
tion techniques assume that all of the information is given at the beginning
of the shell. This requires a slight modification of the technique. In
effect, the modification consists of starting out with initial values of
unity for the six variables N_φ, M_φ, ... β_φ, one by one. The shell equa-
tions are then integrated across the shell to get six equations relating
the values of the variables at the final end to unit values at the initial
end. (If there is pressure on the shell, one more integration is necessary
to obtain the particular solution.) Since three values of the variables are
known at each end, the remaining six unknown values are obtained by solving
the six equations.

The Multisegment Approach

When the shell is too long the matrix of the six equations becomes
very nearly singular and they cannot be solved for the six unknown parameters.

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Kalnins[20] and others have overcome this deficiency by first breaking the shell into shorter segments. The shell equations are integrated over each shell segment in just the same way as above to get six equations between the stresses and displacements at each end of each segment. Then the equations for all the segments are solved simultaneously with the equations of continuity for stress resultants and displacements between the segments and the boundary conditions at the ends of the shell to obtain the solution of the entire shell. A detailed description of this phase of the solution is given by both Cohen[23] and Kalnins.[20] Use of this multisegment approach eliminates the loss of accuracy of the direct-integration approach and permits the analysis of long shells.

It is noted again that the numerical-integration technique can be applied to Equations (19) through (24) without any further simplification. Therefore the only restrictions in the types of problems that may be solved are the restrictions imposed in deriving the equations themselves (i.e., small deflections, thinness of the shell, etc.). This means, for instance, that the thickness and elastic properties can be allowed to vary in an arbitrary manner over the length of the shell. It was pointed out earlier that the same technique is used for solving the more complicated problems of non-symmetric loading except that there are 8 equations as shown by Kalnins. Again, for orthotropic shells, the same technique is applicable although the equations are complicated still further as shown by Cohen. It appears, therefore, that the direct-integration technique is the most accurate and universally applicable technique available for solving problems involving shells of revolution, such as bellows and diaphragms.

DESIGN PROCEDURES

Little is known about the details of the procedures used by manufacturers to design bellows and diaphragms. Because it is difficult to predict the performance of new configurations, the ability to develop satisfactory designs directly affects the competitive position of a company, and the methods used to establish design details are considered proprietary. However, manufacturers have been willing to discuss certain aspects of their design procedures and some information has been gained from the literature. This section outlines the general design procedures which appear to be in use by manufacturers.

Design Procedures for Bellows

Manufacturers must predict the following bellows performance characteristics: (1) stresses and deflections, (2) spring rate, (3) effective area, (4) pressure drop, (5) instability, (6) resonance, (7) corrosion, and (8) operational life. All manufacturers request the opportunity to design or select the proper bellows for each application because of the many factors that must be considered. However, approximate performance characteristics for standard bellows are available to potential users in company brochures, and design nomographs are sometimes included. One company offers a design slide rule, while another company provides extensive design charts. The procedures used by the manufacturers to produce these design aids and to design specific bellows are discussed briefly.

Stresses and Deflections

The general method used by manufacturers in developing design procedures for predicting stresses and deflections is to select form the literature a theoretical approach which most closely approximates the type of bellows to be manufactured. Available approaches (some of which are discussed in the previous report section) are based on plate, beam, or shell theory. Because the approaches are complex and do not usually describe accurately the bellows to be manufactured, most companies have simplified and modified the theoretical analyses of particular configurations.

When a theoretical approximation has been selected, the company produces bellows of the type to be manufactured and the performance of the actual bellows is compared against the theoretical prediction. Stress-coating analysis and strain-gage readings on bellows are common means of analyzing actual stresses. Empirical correction factors are then formulated to make the theoretical approximation agree as closely as possible with the stresses and deflections of the actual bellows. The empirically modified design procedure is then used to design similar bellows.

The most detailed nonproprietary design procedure available has been developed by Atomics International.[6] The basis for the procedure is discussed at length, and design calculations are presented for three configurations, i.e., (1) U-shaped, (2) U-shaped ring-supported, and (3) toroidal. Comparison of the results of the calculations with bellows produced by any given company would probably indicate the need for empirical correction factors for the bellows produced by that company.

Many companies have accumulated experience with a large number of bellows sizes and types, and have developed extensive design relationships which can be used to predict the stresses and deflections of bellows similar to those that have been produced. However, if any company undertakes the production of a substantially new bellows configuration, it is at present necessary to conduct extensive laboratory tests to establish new empirical correction factors for the theoretical approximation.

Some companies have begun to use computers to assist in bellows design. In general the computer programs have been limited to the automation of existing design procedures. A few companies have utilized computers to incorporate some of the basic theory, and it is expected that further development of the theory will result in a wider use of computers for designing bellows.

Spring Rate

Although the theoretical approaches used to predict stresses can also be used to predict spring rates, the spring-rate predictions may be even less accurate than the stress predictions, because spring rate is affected by

inaccuracies in all of the convolutions, while maximum stress is a result of effects peculiar to each convolution. In most cases, manufacturers predict the spring rate of a bellows by means of equations derived from the measured spring rate of a similar bellows. If an accurate spring-rate value is needed, it must be measured for each bellows. The effect of hysteresis is almost always determined by actual spring-rate measurements, rather than by prediction.

For approximating purposes, most manufacturers list spring rates for standard bellows sizes and materials. In the literature, Blair[27] gives a generalized spring-rate formula with typical exponential values. Matheny[28] presents spring-rate formulas for seven typical bellows convolutions, and the design procedure described by Anderson[6] includes both axial and rotational spring-rate calculations for three bellows convolutions. These relationships are useful for approximating the spring rates of certain configurations.

Effective Area

If there is a pressure differential across the bellows, the bellows acts like a piston, and the area over which the pressure apparently acts is known as the effective area. The effective area is approximately equal to an area calculated from the mean diameter of the bellows. Manufacturers' brochures normally give the effective area for standard bellows. However, when this quantity must be known accurately (for example, for face seals) the effective area is measured for each bellows. For some welded bellows, the effective area changes with extension and compression.

Pressure Drop

Most manufacturers estimate pressure losses in bellows and flexible metal tubing from test data or from calculations based on flow through a pipe with an assumed equivalent length or an assumed roughness factor. Daniels[29] describes the calculation of pressure losses based on an assumed roughness factor for two-inch and three-inch annular and helical flexible metal hose.

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Hawthorne[30] presents a relatively new method of calculation based on the assumption that the convolutions behave as uniformly spaced orifices and that pressure drop is caused by a succession of individual flow expansions. This approach has been investigated in some detail at Flexonics.

For internally linked bellows, Daniels[31] presents experimentally determined pressure-drop factors for two types of assemblies: the chain-link type, and the gimbal-ring type. This article exemplifies the empirical approach which is often used by manufacturers to determine bellows performance characteristics in place of a more complicated and perhaps less accurate theoretical approach.

Instability

A bellows may become unstable as a result of internal pressure if the ratio of bellows length to diameter is greater than one, or if the bellows is offset or angularly deflected. As far as can be determined, these conditions are not predicted theoretically by most manufacturers. If there appears to be a possibility of instability, tests are conducted with the bellows of interest mounted for the test as it would be in operation.

In 1952 Haringx[32] developed a method for calculating the pressure at which a bellows may become unstable. He concluded that the pressure buckling of a bellows is closely analogous to the buckling of an axially loaded column. Although this approach has been referenced by subsequent discussions of instability and is recommended by Winborne[8], there is little evidence that the method is widely used by the manufacturers. Newland[33] has very recently extended Haringx' theory to the more complicated case of the universal bellows assembly, i.e., two bellows with a common connector. The accuracy of this approach is not known. Recent investigations by Seide[34] and Anderson[6] concerning the instability of bellows under internal pressure when angularly deflected have produced some interesting results. However, it is not known whether this work is used by manufacturers.

Resonance

A bellows may be placed in resonance by vibration from the supporting structure or by movement of fluid through the bellows. Flow-induced

vibration, which usually occurs in gaseous systems, is predicted from test data. Approximations for resonance due to forced vibrations can be made by calculations based on the bellows functioning as a spring. Vail[35] discusses the calculation and laboratory evaluation of the effect of extension, compression, and fluid damping on the resonance of a welded bellows. An experimental and theoretical investigation of the forced vibration of bellows was included in a study by the Bell Aerosystems Company[36]. Both longitudinal and beam modes of vibration were considered. In addition, consideration was given to a vibration mode in liquid-filled bellows caused by the pumping action of the opening and closing of the individual bellows convolutions as they deflect. In general, however, the vibration characteristics of bellows and structures are sufficiently difficult to predict that laboratory tests of each installation are normally required to demonstrate the susceptibility of the configuration to resonance. Rekate and Schwartz[37] describe such an investigation.

Corrosion

Bellows material is so thin that corrosion rates such as those associated with the chemical industry cannot be tolerated, and highly corrosion-resistant materials must be utilized. However, highly corrosion-resistant metals may suffer from one or more of the following: (1) crevice corrosion, (2) galvanic (dissimilar metals) corrosion, (3) corrosion fatigue, and (4) stress-corrosion cracking.

In bellows design, care is exercised to eliminate crevices and other areas where moisture and other environments might be trapped. Attention is given to the elimination of couples, particularly those having widely different galvanic properties. Such metals, although highly resistant when used individually, may be incompatible when used together. Corrosion can also reduce the fatigue limit of many metals, and this factor must be considered. Many aerospace materials, especially the high-strength alloys, are susceptible to stress-corrosion cracking in environments such as humid air and chloride-containing atmospheres. Configurations are designed to keep residual and applied stresses below those known to promote cracking in specific environments.

Operational Life

In the absence of corrosion (and neglecting creep in high-temperature applications) the operational lifetime of a bellows is determined by its ability to resist failure by fatigue under repeated stressing. The fatigue lifetime of a bellows is difficult to predict from fatigue data usually available for the bellows material. The available material data are often in the form of S-N curves from constant-amplitude uniaxial stressing of specimens in a well-defined metallurgical condition and with good surface finish. Operational behavior of the bellows may involve:

1. Complex loading: cycles of varying amplitudes of pressure or of deflection, or of both

2. Complex stress distributions: varying degrees of biaxiality and of stress gradient at various locations in the material; details are not always easily computible from the applied loads

3. Complex effects of fabrication: varying surface conditions, residual stresses and amounts of cold-work.

There is no satisfactory theory for including all of these complexities.

Accordingly, semi-empirical rules are used for preliminary design. These vary in degree of sophistication among the various manufacturers. The rules often include such simplifications as:

1. Neglect of, or very crude allowance (by some sort of strength-reduction factor) for fabrication variables

2. Use of such approximations, in fatigue-strength analysis, as a maximum stress (or a maximum shear-stress) criterion of failure, a linear Goodman-diagram, a Miner-Palmgren cumulative damage rule.

For design to resist low-cycle fatigue, there is increasing use of the rules being developed for pressure vessels (see, for example, Ref. 38). There are divergencies among manufacturers and users in details of approximations and even in nomenclature.

Similar rules, with one or more coefficients to be evaluated from load-cycling tests on typical bellows are used to provide more realistic operational-life-prediction charts. Such charts may be developed in terms of percent of maximum allowable deflection and of percent of maximum allowable

pressure. If there is a reasonable amount of experimental data, the charts may be quite dependable for interpolation; however, the empirical nature of the guiding rules makes undependable extrapolation beyond the conditions of test. Moreover, although charts from various companies may be similar in appearance, predictions are often applicable only to bellows for which a chart was developed.

Design Procedures for Diaphragms

Performance characteristics for diaphragms are not generally available to potential users. Not only are the diaphragm design procedures of manufacturers considered proprietary, but most diaphragms are fabricated and used in components by each manufacturer, and there is generally no requirement for a component user to be concerned with the diaphragm. However, diaphragm manufacturers welcome the opportunity to design special diaphragm configurations.

The design of diaphragms, as with bellows, presently involves a combination of analytical and experimental approaches. In the analytical approach, equations are derived relating the load-deflection characteristics to the geometry of the diaphragm and the elastic constants of the material. The experimental approach is to make diaphragms of various sizes, shapes, and materials and to load them in various ways and measure their deflection, drift, and hysteresis. From judicious selection of sizes and shapes for experiment, it is possible to deduce design criteria and generally applicable formulas which may be used to design other diaphragms of similar shape and materials. Information available in the literature on each of these approaches is summarized briefly below.

Analytical Approach

Although mathematical description of the performance of corrugated diaphragms of arbitrary shapes is difficult, considerable analysis has been carried out for diaphragms with concentric circular corrugations subject to uniform loading. Two approaches have been taken toward the difficult application of shell theory to such configurations. One involves the use of shell

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theory directly. The other involves simplifying physical assumptions such that approximate calculations can be made.

Application of Shell Theory. The first attempt of this type was made by Grover and Bell[4] by piecing together known approximate solutions to the shell equations for elementary meridional shapes having constant curvature. Their results gave information for stresses and moments, but not for displacements. Wildhack, Dressler, and Lloyd[2] subsequently developed an analysis procedure involving the use of a digital computer and computed stresses and deflections for the configuration investigated by Grover and Bell. This procedure, which is based on exact elastic-shell equations, can be used to analyze stresses and displacements for any corrugated diaphragm having arbitrary meridional shape. Dressler[39] then described the investigation of the Grover-Bell configuration for thin, medium, and thick material by means of the computerized analysis method. This paper shows how thickness influences the coupled bending and stretching quantities in the diaphragm.

Use of Simplified Physical Assumptions. In this approach approximations are made such that algebraic solutions are feasible. In 1940, Charron[40] described two diaphragm types which were determined by the corrugation shape. He theorized that in both types, the elastic stress which corresponds to a definite deflection of the diaphragm increases in approximate proportion to the thickness of the metal. In 1947, Pfeiffer[41] described a hypothetical model for the distribution of stress in diaphragms. It is constructed of members in series, with each consisting of one flexural and one tension spring acting in parallel. This hypothetical model leads to a correlation between pressure on the diaphragm, corresponding diaphragm deflection, effective diameter, thickness, and "plate modulus", a measure of elasticity.

An ingenious approach by Haringx is based on the analysis of a fictitious flat plate which is "equivalent" to the corrugated diaphragm. In three successive papers[42,32,43] he calculated the rigidity, the stresses, and, for large deformations, the degree of nonlinearity of the relation between deflection and load. Subsequently, Haringx[44] described further how the introduction of a few simplifying restrictions leads to the concept of a

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design chart which can be used to give the dimensions of a diaphragm to meet specified requirements. A design chart is given, and the solution of a design problem is described. This chart is very useful for approximating diaphragm configurations. In 1956, Flindt[45] extended Haringx' theory to include the calculation of the thrust which can be exerted by a restrained diaphragm under uniform pressure conditions.

In 1958, Akasaka and Takagishi[46] analyzed the natural frequencies of the corrugated diaphragm as an equivalent flat plate, and derived approximate formulas for the lower-order frequencies of symmetric and asymmetric modes including the effect of the concentrated mass at the center of the diaphragm. Experimental results agreed well with the theory.

Experimental Approach

The literature contains the results of two primary sources of experimental work: (1) the investigations at the National Bureau of Standards, and (2) work at the Taylor Instrument Company.

The National Bureau of Standards has maintained an interest in diaphragm design for many years and has cooperated with other government agencies and industry in several investigations. The results of the major experimental work are summarized in the paper by Wildhack, Dressler, and Lloyd[2]. The pressure deflection characteristics of corrugated diaphragms are correlated by methods of dimensional analysis. Experimental results indicate that the performance for diaphragms of any given shape may be computed from a dimensionless formula derived from experimental data on other diaphragms of that shape. The dimensionless formula is given, and its application to various diaphragms is discussed. Although this work has been relatively extensive, it is not known whether the results have been of value to diaphragm manufacturers.

The most complete discussion of diaphragm design contained in the literature is presented by Newell[1]. Much of the information is based on experimental work conducted at Taylor Instrument. An effort was made to show how diaphragm characteristics are affected by changes in material, dimensions, and treatment. The first part defines a diaphragm and its performance

characteristics; methods of measuring and representing the characteristics, and ways of using them. The second part deals with ways in which diaphragms can be constructed and how various design details and treatments affect performance characteristics. This manual is probably as clear an indication as can be obtained of the design procedures used by diaphragm manufacturers.

The extent to which the service performance of bellows and diaphragms achieves the design predictions is strongly dependent upon the quality of the materials from which they are fabricated and the care taken in their manufacture. Material defects, weld discontinuities, forming irregularities, and postfabrication damage can all result in locally high stresses that may lead to premature failure. In this section, the present state of the art with respect to materials, manufacturing methods, and inspection will be discussed.

Materials

Typical materials for formed, welded, and deposited bellows are discussed. So many materials are suitable for machined bellows that they are not included. Diaphragms can be made from any of the materials listed for formed, welded, and deposited bellows.

Formed Bellows Materials

Materials for formed bellows, shown in Table 3, must be weldable and formable. Although smaller bellows are usually made from seamless tubing, most bellows over an inch or two in diameter are made from sheet or strip formed into a cylinder and longitudinally seam welded. Whether the strip or sheet is purchased to any special tolerances depends upon the end application of the bellows. When the spring rate is not critical--bellows intended for expansion joints, for example--the customary 10 percent mill thickness tolerance is satisfactory. When the deflection characteristics must be more carefully controlled, materials may be selected from warehouse stock. In this way, thickness may be controlled to within about 5 percent on a given order. Rerolled materials from specialty metal fabricators provide the best commercially obtainable thickness tolerances. Bellows manufacturers using rerolled materials claim thickness tolerances of ±0.0001 inch. A more commonly quoted tolerance is ±0.00025 inch over a 20-inch strip width.

TABLE 3. TYPICAL FORMED-BELLOWS MATERIALS

Alloy	Crystal Structure
Solution-strengthened alloys	
Alpha brass	Face-centered cubic
Copper	"
Stainless steels, Types 304, 321, 347	"
Titanium, commercially pure and Alpha alloys	Hexagonal close packed
Inconel	Face-centered cubic
Precipitation-hardened alloys	
Beryllium copper	Face-centered cubic
Inconel 718	"
Aluminum, 7075 alloy	"
Transformation-hardened alloy	
Titanium, Alpha-Beta alloys	Hexagonal close packed - body-centered cubic

Opinions differ among manufacturers as to the desirability of a bright surface finish on the starting material. Some manufacturers note an improvement in the fatigue life of bellows produced from bright-finished material (No. 2B finish), while others see no difference. Some manufacturers also claim that the bright-finished material, containing more cold work than the dull, or matte-finished material (No. 2D finish), is more difficult to form. There is a trend toward the use of bright-finished material arising from the alleged tendency of inspectors to pass shiny bellows and reject dull bellows.

Although there is some disagreement, most manufacturers see no effect of "grain", or preferred orientation, in their starting material. The common materials from which formed bellows are fabricated, when produced under good control, are nearly isotropic, so preferred orientation does not appear to be a serious problem.

Welded-Bellows Materials

Materials for welded bellows need not have the formability of materials for formed bellows. Therefore, in addition to the materials cited above for formed bellows, a variety of less tractable alloys is commonly used for welded bellows. Table 4 shows typical welded-bellows alloys.

Welded bellows are produced in considerably smaller quantity than formed bellows and tend to be used in more specialized applications. All of the alloys itemized in Table 4 for example are heat-resistant alloys. Use of rerolled, bright-finished starting materials is standard in the welded-bellows industry.

TABLE 4. TYPICAL WELDED-BELLOWS ALLOYS

Alloy	Crystal Structure
Precipitation-hardened alloys	
Inconel X	Face-centered cubic
Rene 41	"
Rene 62	"
17-7 PH	"
17-4 PH	"
PH 15-7 Mo	"
M-252	"
Waspaloy	"
Uiimet 700	"
Solution-strengthened alloys	
19-9 DL	Face-centered cubic
A-286	Body-centered cubic

Deposited-Bellows Materials

Materials for deposited bellows are made by electroplating or chemical deposition. The most common material for electrodeposited bellows is nickel. Copper is also used. Chemically deposited bellows can be made from alloys which, though still over 90 percent nickel, contain significant

percentages of other strengthening elements. Both types of deposited bellows can be made with composite metal walls consisting of layers of different metals. The deposited-bellows industry is relatively young, and further developments in deposited-bellows materials can be expected.

General Material Limitations

All manufacturers of bellows and diaphragms use relatively small tonnages of material. Consequently, they are able to purchase only materials melted according to usual commercial practice. Stainless steels, for example, are from electric-furnace melted heats. Although the metallurgical quality of stainless steels is good by ordinary standards, it is likely that some improvement of bellows performance could be achieved by the use of vacuum-melted materials with their lower inclusion contents. Such materials have become standard in bearings. Quantity purchase of heats of vacuum-melted or otherwise specially treated materials by large users of bellows, and release of these materials to bellows manufacturers might be a method of significantly improving uniformity and quality of bellows throughout the industry.

Manufacturing Processes

There are four primary kinds of bellows: (1) formed, (2) welded, (3) deposited, and (4) machined. Typical processes for producing these bellows and for producing diaphragms are discussed briefly. Because the competitive positions of bellows and diaphragm manufacturers are significantly affected by differences in manufacturing techniques and equipment, it is not possible to determine the details of the manufacturing processes. However, it is believed that sufficient information has been obtained for the purposes of the program and for this report.

Formed Bellows

A flow chart for manufacturing formed bellows is shown in Figure 3. The process begins with a thin metal cylinder. For small bellows, the metal

```
                    ┌─────────────────────┐
                    │    Form Cylinder    │
                    └─────────────────────┘
  Clean ──────────────────────►│
                    ┌─────────────────────┐
                    │        Weld         │
                    │  (Unless seamless)  │
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │  Planish Weld Seam   │
                    │     (Optional)      │
                    └─────────────────────┘
  Clean ──────────────────────►│
                    ┌─────────────────────┐
                    │   Assemble Plies    │
                    │   (if multi-ply)    │
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │  Form Convolutions  │◄───┐
                    └─────────────────────┘    │
                              │                 │ Repeat if necessary
                    ┌─────────────────────┐    │
                    │   Process Anneal    │────┘
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │     Final Form      │
                    └─────────────────────┘
  Clean ──────────────────────►│
                    ┌─────────────────────┐
                    │   Set Convolution   │
                    │       Spacing       │
                    │(if required by process)│
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │ Partially End Weld  │
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │  Final Heat Treat   │
                    │    (if required)    │
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │  Complete End Weld  │
                    └─────────────────────┘
  Clean ──────────────────────►│
                    ┌─────────────────────┐
                    │      Inspect        │
                    └─────────────────────┘
```
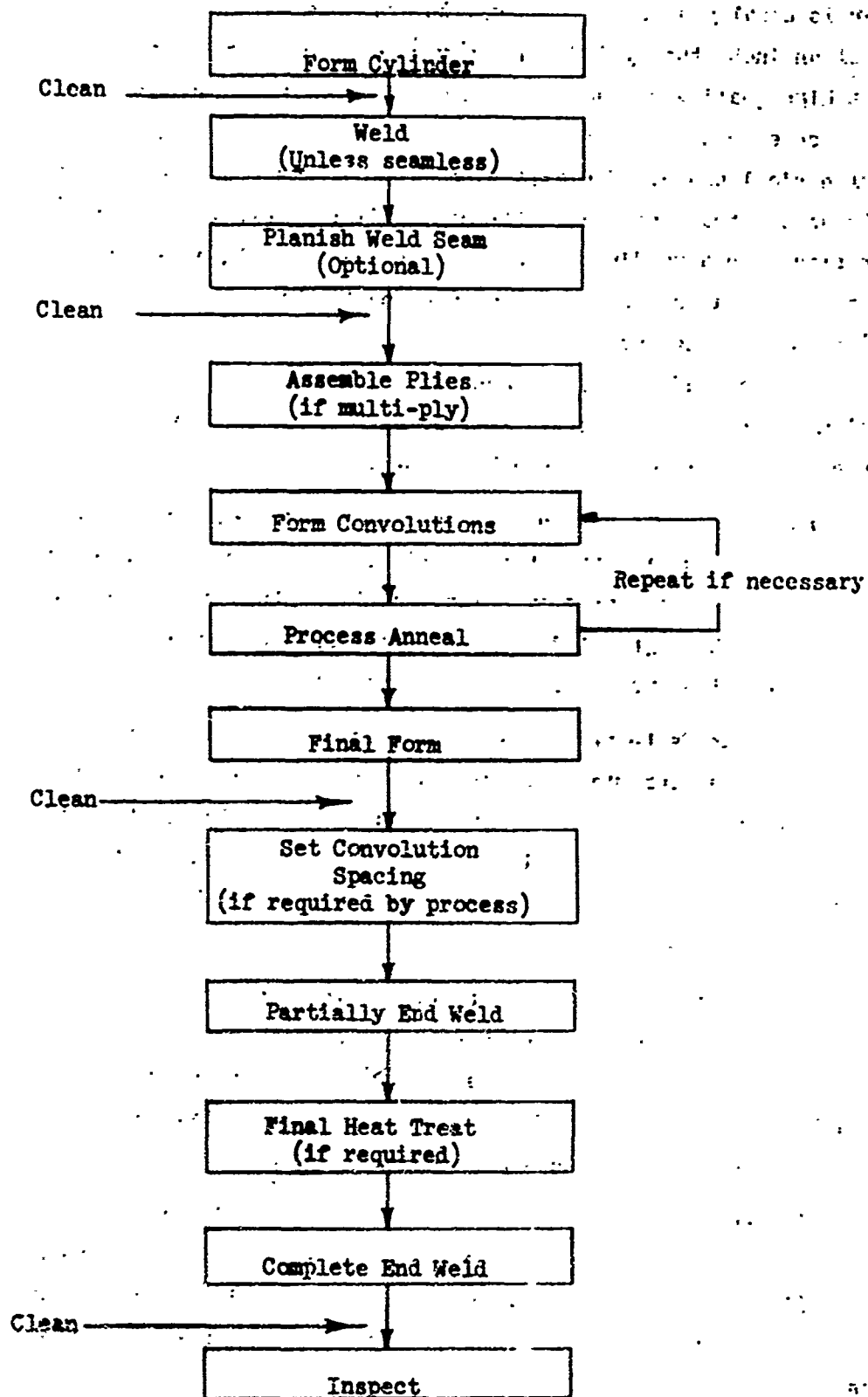
FIGURE 3. MANUFACTURING FLOW SHEET--FORMED BELLOWS

cylinder is usually a seamless tube. For bellows having diameters much in excess of an inch, the cylinder is fabricated from flat sheet, or strip, having a high-quality surface and containing no visible damage to the edges. After the sheet has been cut to size by a shearing operation, it is roll-form to a cylindrical shape. Typically, the cylinder is somewhat overformed in order to assure that the edges will meet satisfactorily. The formed cylinder is then placed in a welding fixture consisting of a rigid backup and hold-down clamps, and a butt weld of the gas-tungsten-arc type (GTA, also known as TIG) is made along the mated edges of the sheet. The technology of making such welds is well advanced, and manufacturers are capable of making welds in material as thin as 0.003 inch. Most welds are longitudinal, but one manufacturer uses a helical weld for small bellows.

Before the GTA welding-process technology had been developed sufficiently to make welds in very thin material, longitudinal weld seams were made using a resistance-lap seam-welded joint. Although some bellows are still made with this type of joint, the overlapped region is a stress raiser and is a potential source of impurity entrapment.

Many manufacturers cold-work the weld zone with a pair of crowned opposed rolls in a planishing operation. Planishing must be carefully controlled in order that the wall thickness in the vicinity of the weld zone is not reduced below the base-metal wall thickness. Some manufacturers do not use planishing because of the danger of wall thinning, while others use it only for certain materials.

In the fabrication of multi-ply bellows, a series of tubes, sized to fit one inside another, are cleaned and assembled ready for the forming operation. The cleaning at this stage is particularly important since it is exceedingly difficult, if not impossible, to remove contaminating materials that have been trapped between the plies once the bellows has been formed.

Almost every manufacturer uses a unique forming machine of proprietary design. Although these machines fall into several basic categories, there are differences in detail which may significantly affect the performance of the fabricated bellows. The basic categories of forming machines are as follows:

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1.   tic, simultaneously formed convolutions
2.   Hydraulic, individually formed convolutions
3.   Hydrostatic, rubber pressure medium
4.   Mechanical rolls
5.   Mechanical expansion tools.

In the hydraulic process with simultaneous convolution formation, the ends of the tube are first closed by movable platens. The end sections of the bellows are constrained in cylindrical dies that may be part of the platens. A series of split rings, one less than the number of convolutions desired, is carefully spaced along the length of the tube. Hydraulic pressure is then applied to the interior of the tube, causing the tube to bulge outward between the split rings.

From this point, processes of different manufacturers differ. Some manufacturers leave the rings in place throughout the entire convolution formation operation. Some manufacturers attach the rings to a pantograph during forming to maintain uniformity. Others remove the rings completely at this point and complete the convolution formation with the tube entirely free of restrictions except at the ends. This latter method is claimed to be advantageous, since it requires a minimum of contact of the tube with metallic tooling. During the formation of the convolutions, the platens must be moved together to accommodate the shortening of the tube. Some manufacturers accomplish the movement of the platens and the regulation of the hydraulic pressure by hand, whereas others have applied automatic controls to the process. Automatic controls are desirable from the standpoint of product uniformity.

It may be necessary to form the convolutions in several stages, depending upon the material and upon the depth of convolution desired relative to the tube diameter and wall thickness. Some manufacturers process anneal their tubes following the initial bulging operation. Others find it necessary to stop several times during convolution formation, remove the split dies, process anneal, and reassemble the tube in the forming machine. Still other manufacturers restrict their product line to convolution depths that can be formed in their materials using a single operation, thus eliminating process annealing.

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... ., since it ...., ...
.... should be held ... a minimum. The .... forming
equipment of some manufacturers per .. .. of forming .. ...en
process anneals than does equipment o. .... .turers.

Some manufacturers form each convolution individually using essen-
tially the same process as described above, but with the hydraulic fluid
confined to that region of the tube where the convolution is to be formed.
The tube is first bulged. Then the external clamp holding the unformed por-
tion of the tube is moved forward a preset distance to form a convolution.
The operation is repeated after the tube is indexed to the next convolution
position. It is claimed that this forming method gives more uniform convolu-
tions than the methods in which convolutions are formed simultaneously.

A variant of the hydraulic process is one in which the hydraulic
oil is replaced by a rubber form. Under pressure, the rubber acts as a hydro-
static fluid. Its use eliminates the presence of oil. If not completely
removed prior to process annealing or final heat treatment, oil can cause
carburiz..... and possible embrittlement of the metal. Residues from oil have
also be... known to cause pit-type corrosion.

Perhaps the oldest method of forming bellows is that of shaping the
convolutions by mechanical tools while rotating the tube. As in the hydraulic
processes, there is considerable variety among the machines for roll forming.
Some roll-form tooling resembles a lathe on which the tube to be formed is
slipped over a centered rotating grooved die. An external tool is then used
to press the tube into the grooves in the die, one groove at a time. Another
type of tooling makes use of two small coaxial wheels over which the tube is
placed. While these wheels are rotated, thus rotating the tube, a third wheel
is brought down between the other wheels, thus forming a convolution. The
tube is then indexed one pitch distance, and the operation is repeated. Con-
siderable ingenuity by the manufacturers who use the roll-forming process
has led to the ability to roll-form the convolutions outward as well as inward.
However, roll-formed bellows are currently in disfavor because of the danger
of creating surface defects, and of smearing metal over these defects in such
a way that they are hidden. A second objection that is often cited to roll-
formed bellows is the excessive wall thinning at the roots or crowns of the

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convolutions that may be encountered if forming is not done carefully enough.
It is reported that some facilities of the National Aeronautics and Space
Administration now refuse to use roll-formed bellows.

Some manufacturers claim to hold the amount of wall thinning during
forming to 5 percent. Others allow 10 to 20 percent thinning. With the
different processes, there will be characteristic percentages of thinning for
any given set of bellows dimensions. The wall thinning is accompanied by
strain hardening of the material and is not directly related to a loss in
strength. The amount of strain hardening for a given amount of thinning
depends in a subtle way upon the precise details of the metal flow during
forming. The relationships of wall thinning, strain hardening, formability
limits, and metal-flow directions are poorly understood as they apply to
bellows fabrication.

When a multi-ply bellows has been formed, one current practice con-
sists of partially closing the ends of the bellows either by resistance seam
welding or GTA welding. The multi-ply bellows is then given an elevated tem-
perature treatment in an effort to remove any contamination from between the
plies. This heat treatment may also be the final aging treatment for the
bellows material. After heat treatment, the end welds are completed, and the
bellows is ready for inspection.

Welded Bellows

The manufacture of welded bellows, as shown in Figure 4, begins
with the blanking of disks, or diaphragms, from sheet material. The blanking
operation must be carefully done using dies that are in good adjustment to
minimize the formation of burrs. Any burrs which are formed on the edges of the
diaphragms must be removed. Depending on the design of the welded bellows,
the diaphragms may be formed into a shape containing one or more circumferen-
tial convolutions. The forming operation is carried out using conventional
metal-working techniques but with careful attention being paid to maintain-
ing the surface finish. Diaphragm thickness is monitored, and diaphragms for
a particular bellows may be preselected for uniformity of thickness.

Pairs of diaphragms are placed together in a welding jig with the
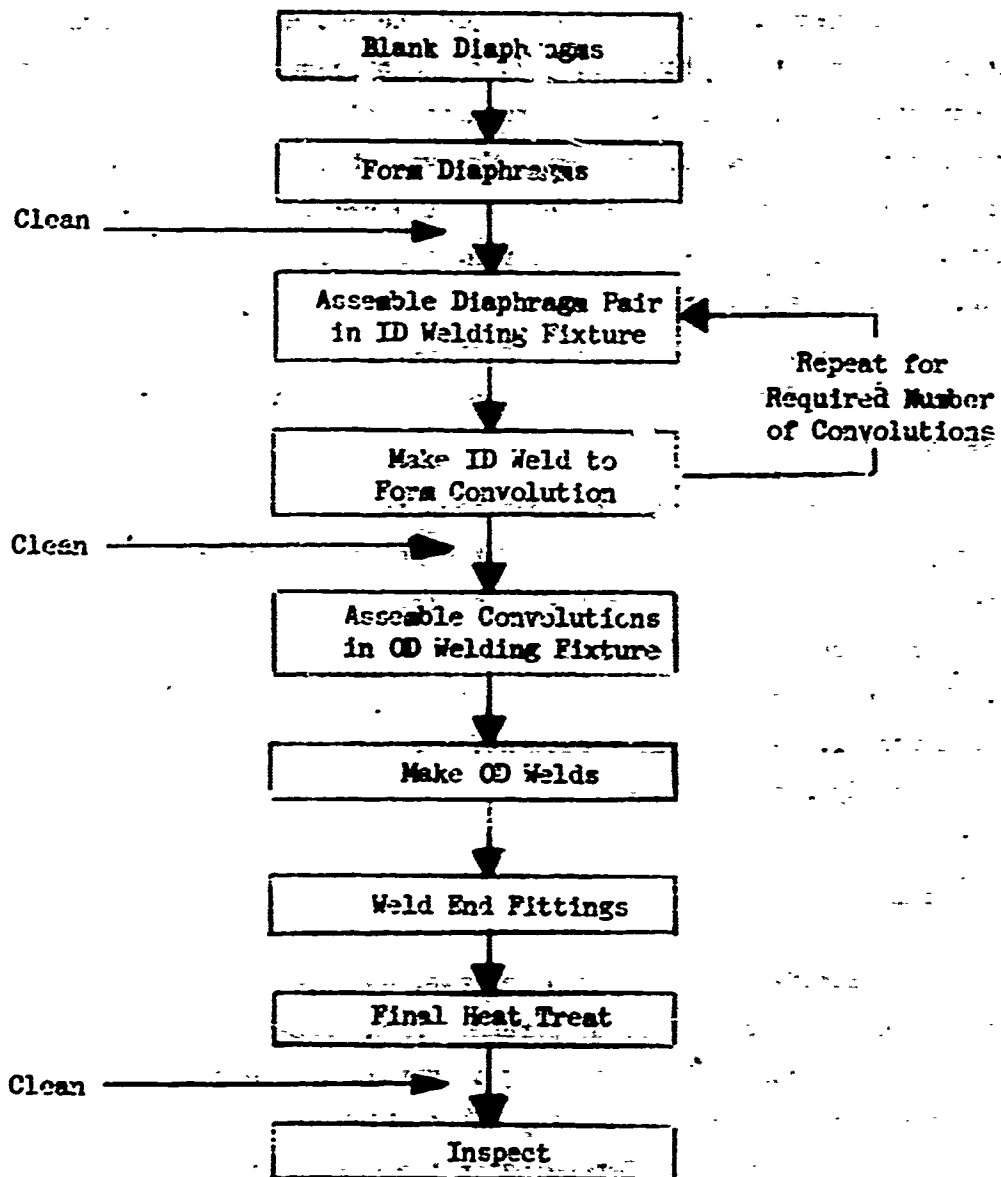inner diameters in contact and clamped with chill blocks on either side of

FIGURE 4. MANUFACTURING FLOW SHEET--WELDED BELLOWS

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the joint. An edge weld is then made around the inner circumference using the gas-tungsten-arc process (GTA). The welded pair of diaphragms is referred to as a convolution. The welding operation is repeated for the number of convolutions desired in the bellows. The convolutions are then stacked in another welding fixture with the other diameters of adjacent convolutions in contact, chill rings being used between the mated surfaces, and the outer diameters are welded in the same manner as the inner diameters.

An alternative method of making welded bellows, adding diaphragms one at a time, does not differ materially from the previously described method except that it might be somewhat faster. In this method, alternate inner-diameter and outer-diameter welds are made until the desired number of convolutions is reached.

Almost all welded-bellows manufacturers use a semi-automatic form of the GTA welding process in which the material to be welded is rotated beneath a stationary torch. Upon completion of the weld, the fixture is moved to the next weld position and the process is repeated. An automatic bellows-welding machine has been publicly announced by G. H. Silver and Associates, Newtonville, Massachusetts, and it is expected to be available for public sale by the end of 1965. It is claimed that this machine will be able to produce welded bellows priced competitively with formed bellows.

Welding difficulties that occur in welded bellows are related to the bellows materials, some of which are not as weldable as the alloys used for formed bellows. Heat-resistant alloys, most of which are vacuum melted, typically contain two or more phases and undergo various solid solution and precipitation reactions during the thermal cycle associated with welding. In some alloys these reactions may result in loss of ductility or strength in the heat-affected zone.

At least one welded-bellows manufacturer has introduced a two-ply welded bellows. Although the manufacturer declined to discuss the details of manufacture, the cleaning requirements for the diaphragms are more stringent than those for conventional welded bellows, and care must be taken to avoid leaving contaminating materials trapped between the plies. Methods of cleaning are similar to those used for formed bellows.

Making of the first weld in a multi-ply welded bellows would appear to present no problems other than establishing proper alignment of the diaphragms

and adjustment of the kick-out of the edges beyond the chill blocks. Since the weld is physical larger than for a single-ply bellows, welding current must be greater. Completion of the second weld, which seals the volume between the two paral el diaphragms, may present serious problems, however, due to blowing of a hole in the weld puddle or leaving a subsurface void at the point of weld clo: re. Among the several methods of overcoming this difficulty are (1) making certain that there are no organic outgassing materials present, (2) increasing the chill-block clamping force to seal gases between the plies so they cannot reach the weld, and (3) use of electron-beam welding in vacuum for the final weld on each diaphragm.

Some manufacturers have made welded bellows using electron-beam welding, but the reported results are not consistent among them. Electron-beam welding is potentially a cleaner process than GTA welding. It would seem, however, that difficulties in making welded bellows are due more to the difficult materials being welded than to the welding process being used.

Deposited Bellows

Deposited bellows are produced, as outlined in Figure 5, either by electroplating or by chemical deposition. Both of these processes offer freedom from several of the restrictions on formed or welded bellows. Very thin walls can be achieved (0.0003 inch), thus resulting in bellows having extremely low spring rates. Bellows need not be axisymmetric and may be of variable cross section along their length. Although the base material for deposited bellows is usually nickel, it is possible to produce chemically deposited bellows of a nickel alloy, and it is possible to use composite wall structures in electrodeposited bellows by plating successive layers of different metals.

Deposited bellows are made on mandrels that have been machined to the precise shape desired, and apparently 6061 aluminum alloy is universally used for the mandrel material. A separate mandrel must be used for each bellows, and the mandrel will be reflected in the structure of the bellows. The expense of machining and finishing of the mandrels to the rigid quality requirements necessary is a major cost item in manufacture of deposited bellows.

After the bellows have been deposited on the mandrels, the mandrels are dissolved away, presumably in an alkaline solution in order not to damage

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          ┌─────────────────────────┐
          │    Machine Mandrels     │
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │    Polish Mandrels      │
          └─────────────────────────┘
Clean ───────────────►│
                      ▼
          ┌─────────────────────────┐
          │  Inspect Mandrels for   │
          │  Dimensions and Finish  │
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │    Prepare Solution     │
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │    Deposit Bellows      │
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │   Etch Mandrel Away     │
          └─────────────────────────┘
Clean ───────────────►│
                      ▼
          ┌─────────────────────────┐
          │      Gold Plate         │
          │      (optional)         │
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │   Solder End Fittings   │
          └─────────────────────────┘
Clean ───────────────►│
                      ▼
          ┌─────────────────────────┐
          │        Inspect          │
          └─────────────────────────┘
```
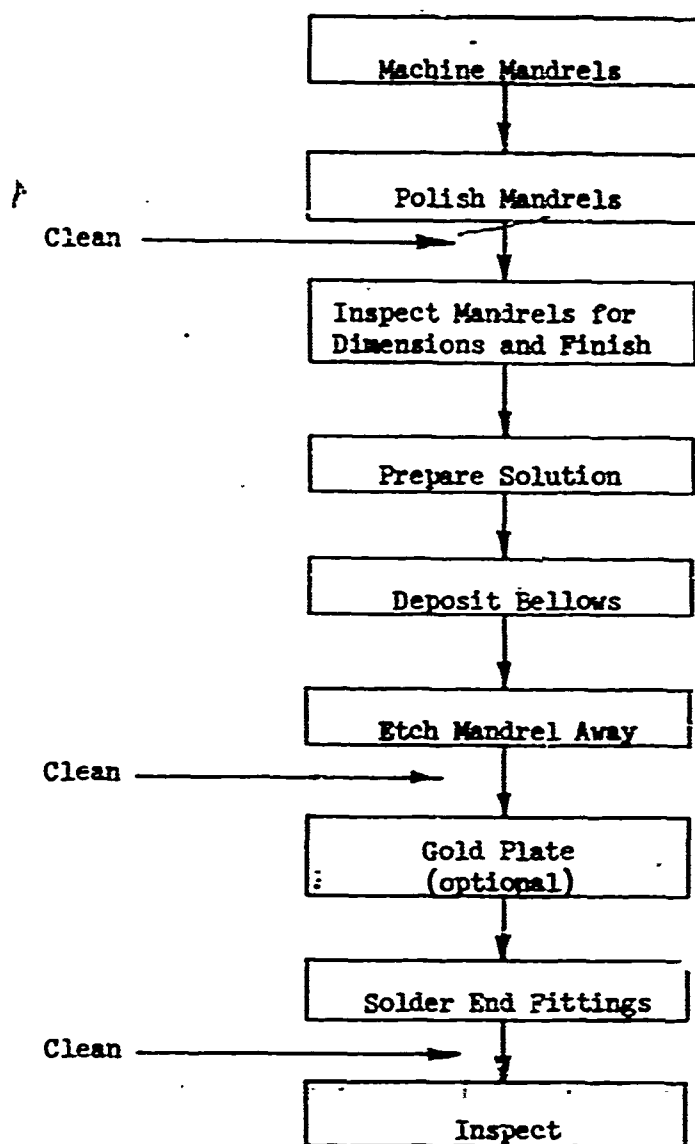
FIGURE 5. MANUFACTURING FLOW SHEET--DEPOSITED BELLOWS

the bellows. The bellows may then be gold plated, although this is not essential, and end fittings are soldered in place. Soldering is used because of the thinness of the bellows walls.

Diaphragms

Diaphragms are constructed by spinning, stamping, or hydrostatic pressure. The spinning is done in a lathe by pressing the metal against a corrugated form. This results in a certain amount of cold working which improves the life of the diaphragm. Some manufacturers stamp the diaphragms first and finish them by spinning.

In the stamping process usually two mating steel dies are used. Some dies are made so that they make contact only with the material on concave sides of the corrugations. The depth can be adjusted through a wide range. The die can be made such that the corrugations are formed in succession from the inside to the outside, thus drawing the material gradually from the outside. In order to reduce friction, a lubricant may be used between the material and the polished die.

The hydrostatic process is similar to the process used to form diaphragms for welded bellows. A metal blank is clamped against the die and hydraulic pressure or pressure from steel-backed rubber forces the blank against a corrugated die. Small bleed holes relieve the pressure between the blank and the die.

The material may be heat treated prior to forming to make the material more easily worked. After formation, the diaphragm may be heat treated to reduce the residual stresses created by the forming operation. The type of heat treatment required before and after forming is a function of the material and of the diaphragm shape.

A single diaphragm may be used or two diaphragms may be fastened together to form a capsule. In either case the diaphragm will be fastened at the outer diameter and suitable fittings will be attached to the center of the diaphragm. A diaphragm used singly may be clamped at its outer edge. Fittings are attached to the centers by a variety of processes including soldering and spot welding. Welding of the diaphragm edges is usually accomplished by GTA welding, although considerable experimenting is being done to adapt electron-beam welding for this purpose. Electron-beam welding is particularly attractive when the diaphragm capsule must be evacuated for service.

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In-Process Inspection

Bellows and diaphragms are inspected during and after fabrication. In-process inspection is intended to detect faulty material, faulty welding, improper convolution formation, handling damage, and lack of cleanliness.

Material Inspection

As described previously, materials for bellows and diaphragms must be very uniform and free from defects. When material is received, it is usually measured and inspected carefully to make sure that there are no large irregularities such as thinning, bulges, wrinkles, and dents, and no surface damage such as nicks, scratches, and pits. Often specimens from each sheet are used to determine the yield strength, ultimate strength, hardness, and chemical composition of the material.

Weld Inspection

Many manufacturers consider the forming process to be an adequate check on the quality of the seam weld. This is particularly true of bellows formed by hydraulic or rubber pressure. The appearance of the weld is usually checked for size and uniformity. In some cases, the weld is checked by radiography. As is explained in the following section, there is considerable disagreement concerning the value of radiographic inspection.

Convolution Formation

Although it is known that shadowgraph equipment is used by some companies for checking convolution shape, the means of checking convolution shape and material thickness are not known in detail because this function is a part of the proprietary aspect of bellows and diaphragm manufacture. However, it is apparent that visual checks and measurement of critical dimensions are used in all cases.

Handling Damage

Extreme care must be taken to assure that the thin bellows and diaphragm material is not damaged during manufacture. Inspection for such damage is done visually.

Cleanliness

Extreme cleanliness is required for aerospace bellows and diaphragms, particularly for multi-ply bellows. The procedure for checking cleanliness depends on the type of cleaning process being used and the cleanliness level required. With multi-ply bellows, a reasonably good check is provided by a postformation heat treatment. If moisture is trapped between the plies, gas expansion causes a bulge in the bellows. However, cleanliness is so important and so difficult to check, that rigid control of the cleaning processes is the best means of achieving satisfactory cleanliness.

Bellows are both inspected and evaluated in performance after fabrication. Some or all of the following procedures may be carried out by the manufacturer as well as by the purchaser.

Evaluation Procedures for Bellows

The primary failure modes for aerospace bellows are: (1) leakage, (2) improper spring-rate characteristics, (3) squirm, (4) fatigue due to excessive magnitude and/or number of applied loads or displacements, and (5) fatigue due to excessive cycling because of vibration. Because failures may be caused by improper design, by material and manufacturing variations, and/ or by unanticipated operational modes, the evaluation procedures are concerned with one or more of these sources of failure. The types of procedure used for any given bellows are determined by the manufacturer and the user.

Physical Examination

Although aerospace bellows are usually manufactured carefully in small quantities, it is still customary to submit each specimen to a physical examination after it has been fabricated. Such an examination is desirable because premature failure can be caused by very small material and manufacturing variations, and such variations may occur even in the most closely supervised manufacturing process. Bellows are commonly inspected by the following procedures.

Visual Inspection. If an unanticipated stress raiser occurs in a highly stressed area, the bellows may fail prematurely. The stresses in bellows are greatly affected by the thickness and shape of the convolutions. A visual inspection of each bellows is usually made to determine that the bellows has been made to the proper dimensions, and to detect changes in bellows shape such as bulges, dents, flats, ridges, and grooves. In addition, measurements are often made to verify that excessive thinning of the material has not occurred at the roots and crests of the convolutions.

Visual inspection is also used to obtain an indication of stress raisers occurring in the surface of the material or in the welds. Because fatigue failures can be greatly accelerated by surface irregularities, the

bellows surface is closely inspected for pits, nicks, and scratches. So important are surface effects that a bellows may be rejected if the appearance of the bellows surface is significantly different from the appearance which is known to be normal for that particular manufacturing method. Welds are inspected for size and uniformity of bead, and for color. Although it is not always possible to detect a poor weld by its appearance, experience has shown that a weld which is irregular or which shows evidence of improper heat application may cause premature failure. The inspection of both the material surface and the welds is often conducted with a liquid dye penetrant to assist in the detection of cracks and scratches.

Visual inspection is also used to verify that the bellows has been cleaned properly. Usually aerospace bellows must be extremely clean and any evidence of dirt or liquid film may be cause for rejection.

Radiographic Inspection. There is considerable disagreement concerning the value of radiography for inspecting bellows. Some companies believe that radiographic inspection of bellows is so difficult as to be ineffectual, while other companies believe that it is a useful, if imperfect, inspection procedure. The value of the procedure depends to a great extent on the size and shape of the bellows being examined.

Leakage

The large surface of thin material and the number of welds make bellows susceptible to leakage. Leakage is usually checked during the proof-pressure test because this is the condition most likely to reveal a leak. Three types of leak tests are common: (1) a bubble test in a liquid, (2) a soap-bubble test, and (3) a helium-mass-spectrometer test.

In the bubble test in a liquid, a gas is used to pressurize the bellows and the bellows is placed in a liquid to determine whether bubbles of escaping gas can be detected. In the soap-bubble test, a soap solution is painted on the surface of a pressurized bellows. The bubble tests are particularly good for liquid systems because it has been shown that a source of leakage which cannot be detected by these methods will rarely leak a liquid.

For gaseous systems, and for liquid systems operating under stringent conditions, the helium mass spectrometer is usually used. This test may be conducted either by evacuating the bellows and surrounding the bellows with helium, or by pressurizing the bellows with helium and "sniffing" the outside of the bellows. In either case, the rate of leakage is usually not measured - any leak being considered cause for rejection.

Spring Rate

The spring rate of a bellows is the summation of the spring rates of each convolution. In addition, the spring rate is approximately proportional to the cube of the thickness of the bellows material. Consequently, excessive spring-rate variation is one of the most sensitive means of indicating improperly formed convolutions or excessive variation in material thickness, and spring rate is a major criterion for comparing the expected performance of a bellows with the laboratory performance of test specimens of the same configuration.

For most bellows operating in the elastic state, the axial spring rate of an unpressurized bellows is linear. If the required loads are small, the spring rate may be measured with dead weights or a load cell. If the loads are large, a universal testing machine is commonly used. It is desirable before taking measurements to "exercise" the bellows several times to obtain a reproducible deflection-versus-load relationship.

Since the axial spring rate is significantly changed if a bellows is pressurized, the spring rate under operating pressures and deflections is also often determined by experiment. This is a more complex test than an unpressurized spring-rate determination because the bellows must be sealed properly and restrained, and accurate pressurizing apparatus is required.

Sometimes it is desirable to measure the spring rate of a bellows offset or angular deflection. It is usually necessary to design special fixtures for each application. In general, the forces required for this type of test are sufficiently low that they are applied with dead weights or a load cell.

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Operational Evaluation

Operational-evaluation procedures consist of operating the bellows under conditions which simulate the most severe operating conditions. Typical tests are concerned with deflection, pressure, vibration, and flow. The tests are often conducted at ambient temperature first and then at operating temperature.

Endurance Cycling - Deflection Only.

Many bellows operate with fluid pressures which are sufficiently low that the stresses due to pressure are insignificant. For such bellows, it is possible to evaluate their operating life by unpressurized deflection tests. It is necessary to duplicate the expected deflection modes and to deflect the bellows a sufficient number of cycles to demonstrate adequate life. It is very difficult to determine how many cycles beyond the expected operating cycles are necessary to demonstrate an adequate design. This is decided for each application by the manufacturer and/or the user.

Endurance-Cycling - Pressure Only.

In some bellows, for example flexible metal hose, the stresses caused by pressure are the only significant stresses. If pressure pulsations are expected in the fluid system, tests are conducted to determine whether such pulsations will cause fatigue failure in the bellows.

Endurance Cycling - Deflection With Pressure.

The most common operational tests consist of deflecting the bellows in the expected operational modes while the bellows is pressurized to the maximum internal or external system pressure. This test produces the highest combined stresses. Cycles equivalent to the expected number of life cycles plus a certain number of additional cycles are imposed to demonstrate adequate life expectancy. When only axial deflections are required, these tests are relatively simple. When a combination of axial, rotational, and/or offset motion is required, the test may become quite complicated.

Vibration.

Because a bellows behaves like a spring and responds to certain frequencies, it is necessary to demonstrate that a bellows will not

respond improperly to the expected vibrations of the system structure and fail prematurely from fatigue or overstressing. The bellows is usually subjected to the amplitude and frequency inputs which represent the conditions expected in the system. A range of frequencies and amplitudes is usually used because of the difficulties of predicting the expected operating values accurately. Occasionally the behavior of the structure is put on tape and the tape is used to drive the vibration equipment.

Flow. The effect of fluid flow through the bellows must sometimes be evaluated. One criterion is the amount of pressure drop caused by the bellows. Another criterion is the susceptibility of the bellows to flow-induced vibration.

Squirm

A bellows with a length-to-diameter ratio greater than one may fail as a column when subjected to internal pressure. The determination of this possibility is usually made during the proof-pressure test.

Proof Pressure

As with all fluid-system components, bellows are subjected to 1-1/2 to 2 times the maximum system pressure to demonstrate a pressure-safety factor. The proof pressure is usually maintained for a period of several minutes.

Pressure Capacity

It is customary to subject a representative bellows to sufficient pressure to cause rupture. Occasionally, note is taken of the pressure at which severe deformation of the bellows occurs, because only large deformations change the subsequent response of the bellows (e.g., spring rate, stroke capacity, fatigue life). Thus the deformation pressure may be the practical maximum pressure capacity.

Postexamination

If a bellows fails to pass one of the above tests, particularly the operational tests, it is necessary to determine whether failure was caused by circumstances peculiar to that bellows, or whether a design or manufacturing change should be made. The postexamination consists of utilizing the procedures described under Physical Examination to determine the cause of failure. In addition, it is common practice to make a microscopic examination of the failed area, and to make a metallographic examination of polished cross sections of the failed material.

Evaluation Procedures for Diaphragms

Diaphragms are usually evaluated only by the manufacturing facility. The component containing the diaphragm may be evaluated by the purchasing facility, but the purchaser is usually not concerned with the diaphragm per se.

The evaluation of diaphragms as instrument devices is described in considerable detail in Newell's "Diaphragm Characteristics, Design, and Terminology".[1] The techniques and equipment described should be adequate for measuring force, pressure, and deflection characteristics for any diaphragms which are to be operated entirely within the elastic state. Many of the procedures described could be used for evaluating small instrument bellows.

The evaluation of diaphragms for other operational modes is not well reported. In the absence of sufficient information, it must be concluded that expected operational conditions are simulated and test specimens are cycled in an attempt to determine operational adequacy. It is assumed that many of the techniques used for bellows are also used for diaphragms.

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6.

Aksel'rad, E. L., "Large Deformations of Corrugated Membranes as Nonshallow Shells", Izv Akad Nauk, SSSR, Mekh i Mash (1), 1964, pp 46-53 (in Russian).

In a previous work, the analysis of small deformation of a membrane with sinusoidal corrugation was based on the solution of equations of a shell. In an expansion of this solution, the problem of calculating nonlinear characteristics is analyzed in this paper. The produced formulas for calculation of deformation of membranes with uniform sinusoidal corrugation are compared with experimental results produced by V. Ya Il'minskiy.

7.

Alesch, C. W., et al., "Prediction of Creep Effects in Aircraft Structures", General Dynamics/Convair Report, February, 1962 (AD 277163).

The method presented in WADD TR60-411 Part I for predicting deformations in aircraft structures undergoing creep is reviewed. Modifications and simplifications of this method are considered, and a simplified version of the original method is presented. Box beam tests were used to investigate the simplified method. The outcome of these tests indicated the accuracy of the method in predicting deformations in aircraft structures undergoing creep was in the same order of accuracy as that usually

experienced in redundant analysis procedures. The power law for expressing creep relations is found redundant in solution. Its usefulness appears chiefly in the display of creep test data. Currently creep prediction methods, such as the Larson-Miller and Manson-Haferd methods, appear as linearizing approximations for creep-relations with the result that inaccuracies in predicting very long and very short creep life restrict their usefulness. An approach to creep prediction based on creep-rupture history for establishment of creep laws is proposed. Relationships between tension- and creep-test data are examined experimentally with respect to single and repetitive load applications. General relationships are examined with the outcome that a general approach to creep prediction in all metallic materials appears improbable.

<u>8.</u>

Anderson, W. F., "Analysis of Stresses in Bellows, Part I: Design Criteria and Test Results", Atomics International Report NAA-SR-4527, October 15, 1964.

Design charts and systematic design forms are presented for simplified calculations to check the number of convolutions and thickness required to limit the deflection-pressure stress range in three types of bellows: (1) convoluted bellows, (2) convoluted bellows with reinforcing rings, and (3) toroidal bellows. The design charts are based on the equations for stresses derived from an asymptotic solution for the equations of toroidal shells found in previously published literature. Proposed stress limitations to be used with the calculated stresses are based on those of the ASA Code for Pressure Piping. Data from 108 fatigue tests at 70 F and 18 fatigue tests at 1200 F for all three types of bellows are presented. These data are evaluated statistically and justify use of the proposed allowable stresses. The conclusion is drawn that expansion-joint bellows can be designed to the same stress levels as other components of a piping system with equal confidence in the reliability of the design.

<u>2.</u>

Anderson, W. F., "Analysis of Stresses in Bellows, Part II, Mathematical", Atomics International Report NAA-SR-4527, May 27, 1965.

This second part of a two-part report presents the mathematical justification of a proposed design analysis method for pipeline expansion bellows. When this study was initiated, three mathematical techniques - namely (a) truncated series, (b) finite difference, and (c) direct analytical functions - appeared to offer sufficiently accurate stress solutions of the differential equations of elastic-shell behavior. (1) The truncated series solutions involved the usual problem of undetermined error resulting from truncating the series; and required eliminating certain important variables to simplify the equations so that solutions could be obtained. (2) Finite difference solutions seemed to require a needlessly great number of segments because the bending stresses can attain their peak

values and start to decrease within 1/6th (15 deg of the 90 deg) of the segment of the toroidal shell section. Also, with the computers available at that time, costs of programming the finite difference equations and of computer time promised to exceed those for the technique selected. (A greater number of important variables, however, might have been reliably investigated by this finite difference technique.) (3) The possibility of obtaining direct solutions of the toroidal shell equations as a boundary value problem, using published values of Hankel functions, had been demonstrated by the work of Clark and Hetenyi and Timms. This technique requires solution of only four simultaneous equations for each combination of variables, and allows inclusion of one important variable that must be omitted by the truncated series solution. Since the Hankel functions are solutions to equations which represent the shell equations asymptotically, a certain error was unavoidable in solving the asymptotic equations at points far from the asymptote. Nevertheless, the direct technique was selected for use when it was observed that compensation for this error could be introduced, to permit reasonably accurate results.

10.

Andreyeva, L. E., "Calculation of a Corrugated Membrane as an Anisotropic Plate", Inzh. Sb., Akad. Nauk SSSR, 21, 1955, pp 128-141 (in Russian).

Existing methods of calculating corrugated membranes have limited ranges of application, since they are applicable only for comparitively small deflections (of the order of 2 - 2.5 times the thickness of the membrane). However, most membranes are deflected an order of magnitude greater than the thickness of the membrane. The thinner the membrane, the greater its relative deflection compared to the thickness and the smaller the region in which the calculated results are valid. In this paper, an approximate method is presented for the calculation of a thin membrane for deflections considerably exceeding its thickness. This method may be used for a membrane with arbitrary periodic corrugations. The method is essentially the same as that used by Haringx.

11.

"Application of Metal Bellows", Machinery(London), 73 (1888), December 30, 1948, pp 887-894.

Brief descriptions are given of the design, manufacture, and use of formed and welded metal bellows. Causes of failure are given, and a chart is presented for estimating the possible cyclic life.

12.

Archer, G. R., "Successful Welding of Foil Gages", Welding J., 39 (4),
April 1960, pp 343-347.

Time-temperature charts are given for the heating of electrical-resistance
spot welds in stainless steel 0.010 in. or less thick: The maximum
temperature is usually reached within the first 1/2 cycle of 60 cps current
flow; a weld forms in the first half cycle and the weld nugget increases
in size for each subsequent half cycle. Variations in welding time (number
of cycles) do not produce pronounced effects on weld strength; but varia-
tions in heat (setting of the welder) are extremely important. Expulsion
of molten metal, if it occurs, usually occurs on the first or second half
cycle. Peak voltages and currents, rather than rms values, are significant.

13.

Archer, R. R., "On the Numerical Solution of the Nonlinear Equations for
Shells of Revolution", J. Math. Phys., 41, September 1962, pp 165-178.

Although the general equations for the finite axisymmetrical deformations
of thin shells of revolution have been available for some time, it is only
very recently that computational procedures have been designed which have
produced detailed numerical results with the aid of digital computers
for significant nonlinear shell problems. It is the purpose of this paper
to set up a procedure for the numerical integration of the nonlinear
shell equations as derived by Reissner, and demonstrate the effectiveness
of this procedure in handling nonlinear shell problems. In particular,
detailed numerical results are obtained for the clamped spherical shell
segment under uniform pressure and the spherical shell segment without
edge moment or horizontal restraint subject to a point load at the apex.

14.

Arkilic, G. M., "Analysis of Toroidal Shells of Semi-elliptical Cross
Section", Ph. D. Thesis, Northwestern University, 1954, 88 pp.

The problem of toroidal shells of semi-elliptical cross section under
axially symmetrical loading and given boundary conditions is treated by
deriving the differential equation from the fundamental equations of thin
shell theory. The complete solution of this equation is obtained by
utilizing the asymptotic forms. After having analyzed the general pro-
cedures of several types of loadings and boundary conditions, some prob-
lems of practical importance are worked out numerically. Of these, the
analysis of stresses and deformations of bellows may be mentioned. In
addition, approximate formulas for maximum stresses and deformations are
established for general engineering use.

15.

Au, T., "Equations for Thin Toroidal Shells", J. of the Aerospace Sci.,
26 (6) June 1959, pp 391-392.

In the analysis of thin elastic shells of revolution having constant
radius of curvature along the meridian, the fundamental equations of equilib-
rium and deformation based on Love-Meissner's assumptions can be reduced

to two simultaneous differential equations of second order. In the cases
of conical and spherical shells, such reduction leads to rather simple
results. For the portion of a toroidal shell which serves as the knuckle
of a toriconical or torispherical head of a pressure vessel, similar
results can be obtained.

16.

Azzi, V. D., "Plasticity - A Survey of the State of the Art", General
Dynamics/Electric Boat Report No. U413-62-006, February 15, 1962.

This report reviews the available literature pertinent to some aspects of
plasticity. Past achievements, present areas of investigation, and possible
future areas of interest are considered. The emphasis is on the present
state of the art of those phases of plasticity broadly classified as
limit analysis, dynamic plasticity, and yield criteria. Research in plas-
ticity has been most active for little more than a decade. It is concluded
that although considerable effort has been expended in the investigation
of those phases of plasticity of interest, and extensive literature is
available as a result of these investigations, much additional research
will be required to bring this relatively young field to a desired stage
of maturity. A bibliography of 264 references is included.

17.

Badawy, E.S.M., "An Investigation of Deflection and Stress Distribution
in Corrugated Diaphragms", Ph. D. Thesis, University of Minnesota, June
1959, 132 pp.

A general analysis of corrugated diaphragms is presented. Expressions
for deflection and stresses have been derived by differential equations.
Additional developments have been made for the deflection of corrugated
diaphragms, subjected to central loads, by dimensional analyses. A com-
plete stress analysis was made for a diaphragm subjected to a central
load. Using the results of this calculation, further recommendations are
made for other diaphragms.

18.

Balakrishna, S., and Srinathkumar, S., "Pressure Transducers Using the
Linear Differential Transformer", Natl. Aeron. Lab., Bangalore, July, 1963
(N64-29389).

A pressure transducer is described which uses a linear variable differen-
tial transformer to sense the displacement at the centre of a diaphragm
subjected to the pressure being measured. Design details of the transducer
are given including complete specifications for the differential trans-
former and the electronic circuit used for indication. The diaphragm
of the transducer is changed to get different full-scale pressure ranges.
The accuracy of the transducer in all ranges is better than ±1 percent.

19.

Barker, R. B., "Pigma Welding - A Method for Reducing Weld Porosity", Welding J., 44, January 1965, pp 1s-6s.

Porosity in welds is greatly reduced when Al is welded with the gas-metal-arc process in a chamber filled with an inert gas to a pressure of 50 psi.

20.

Barnby, J. T., "Effect of Strain Aging on the High-Temperature Tensile Properties of an AISI 316 Austenitic Stainless Steel", Iron and Steel Inst. J. 203 (4), April 1965, pp 392-397.

The appearance of jerks in stress/strain curves during high-temperature tensile testing, and of initial yield points in room-temperature tensile tests, shows that strong locking of dislocations can occur in AISI 316 austenitic stainless steel. An increasing rate of work-hardening with increasing temperature, coincident with jerky stress/strain curves, is interpreted as due to dynamic strain aging of dislocations which become strongly locked by carbide precipitation upon them.

21.

Baskevitch, N., "Effective Area of Diaphragms", Machine Design, 30, August 7, 1958, p 124.

Formulas are presented for determining the effective area and effective diameter of circular diaphragms. The formulas are derived by treating the diaphragm as a uniformly loaded trapezoidal beam.

22.

Beard, C. S., "Positioners for Diaphragm Actuators", Instruments and Automation", 29 (9), September 1956, pp 1782-1783.

Valves must be positioned accurately to function as precise control elements. Brief descriptions are given of valve positioners using bellows and diaphragms to impart sensitivity to the valve and to insure accurate positioning as dictated by the control signal.

23.

Bell, W. J., and Benham, P. P., "The Effect of Mean Stress on Fatigue Strength of Plain and Notched Stainless Steel Sheet in the Range from 10 to 10^7 Cycles", DMIC-49613, Battelle Memorial Institute, October 1962.

Stainless steel sheet (18 CR - 9 Ni) was tested in fatigue under axial-load cycling in plain and notched conditions. Various stress ratios R were used, ranging from R = -1.0 to +0.91, and cyclic lifetimes of from 10 to 10^7 cycles were covered using testing frequencies of 5 to 15 cpm and 3,000 cpm. The effect of mean stress on notch fatigue strength could not be predicted empirically solely from unnotched material data; at least one notched fatigue curve is required. A fatigue strength reduction factor

based on maximum stress for a particular mean stress and endurance provided the most reliable correlation between unnotched and notched data. Simple functions existed in the low-cycle region between stress range and plastic strain range, and between total energy and cycles-to-fracture; both functions were largely independent of stress ratio.

24.

Bell Aerosystems Co., "Research on Zero-Gravity Expulsion Techniques, Final Report", No. 7129-933003 March 1962 (AD 274044).

Design concepts are presented of zero-gravity expulsion devices on an extremely broad basis and a compendium is formed of such device configurations as an aid to system designers. in the selection of expulsion systems for particular applications. As a supplement to the concept presentations, the report also presents some of the more important data necessary for design with emphasis on information not readily available in current literature.

25.

Bell Aerosystems Co., "A Study of Zero Gravity Positive Expulsion Techniques", Report No. 8230-933004, June 1963 (N63-19964).

This report summarizes the results of a 10-month program conducted by the Bell Aerosystems Company to fulfill three prime objectives: (1) To evaluate metallic positive expulsion devices applicable to rocket propulsion systems, (2) To conduct design and integration analyses of the expulsion device considered to offer the highest potential for application to manned space flight and for which a broad base of engineering design data were lacking and not in the process of being generated under any other known program, and (3) to design, build, and evaluate an apparatus to measure propellant permeation rates through typical nonmetallic materials used in positive expulsion devices. It was established that a substantial body of engineering design and tank integration data were already in existence, or were being gathered both for nonmetallic expulsion devices and for non-conventional systems such as those using surface forces, dielectrophoresis, and acoustics. On the other hand, the ex_sting body of engineering data covering metallic expulsion devices was found to be rather meager. However, metallic expulsion devices offer a greater potential for manned space flight because of their ability to withstand a wider range of operating temperatures and radiation dosages than nonmetallic systems.

26.

Bell Aerosystems Co., "Study of Zero-Gravity Positive Expulsion Techniques", Interim Report No. 8230-933007, April 1964.

This report summarizes the work of a 10-month continuation effort under the basic NAS7-149 program. The major tasks considered for this follow-on effort were: (1) structural investigation of metallic bellows; (2) dynamics investigation of metallic bellows; (3) permeation technology; and (4) optimum envelope investigation. The report discusses the modifications

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incorporated into the structural analysis of bellows which was started during the basic program. Also presented are results from a preliminary study of the effects of variation in geometric parameters. The dynamics analyses of bellows include a comparison of the bellows.accordion mode and the general case of a longitudinal homogeneous bar fixed at both ends. A mathematical model for the liquid modes was also developed. This porous-bar concept demonstrated good agreement with test data. Results of an experimental test program to determine the dynamic characteristics of double-ply bellows are included. The permeation work was a continuation of the investigations initiated during the original program on detectors. As a result of this work, the thermistor-type detector was selected as the most practical. Both the design and the application of this detector are discussed. A new permeation chamber, using a corrugated diaphragm in place of a bellows, is discussed and the results of development testing with this apparatus are presented. A series of graphs is presented for use in selecting the lightest weight bellows assembly.

27.
Bell Aerosystems Co., "Study, Design and Test of Functionally Integrated Pneumatic Components for Rocket Propulsion Systems", Edwards Air Force Base Tech. Rept. No. AFRPL-TR-65-93, June 1965.

An investigation was made of helium pressurization functions in propulsion systems for several classes of vehicles. Techniques of performing the functions of fill and drain, filtration, start, pressure regulation and relief were studied and concepts of integrating and combining these functions were evolved. The concept of integration of functions was implemented through the design and fabrication of two integrated pressurization components for service with fluorine and methane gas pressurants. Design characteristics included nickel-beryllium seats and poppets, monel cladded solenoid with solid-state current limiter, metal dynamic and static seals, common relief and regulator spring and bellows, and Monel 5 micron filter. HF corrosion tests were conducted on nickel-beryllium and Inconel specimens. Leakage, response, and endurance tests were conducted on the solenoid start valve which incorporated a nested plate bellows made of Berylco Nickel 440. Performance tests were made on the relief valve which contained a hydroformed bellows made of 3-ply 0.003-in. Monel. Steady-flow and dynamic-flow performance tests were conducted on the pressure regulator which incorporated an externally pressurized hydroformed "Omega" bellows made of Inconel X. Finally, performance tests were conducted on the prototype integrated pressurization components to verify their design and ascertain achievement of performance objectives.

28.
"Bellows Give Flexibility With Strength", Engineering, 193, March 23, 1962, pp 336-387.

A brief description is given of the use of metal bellows for providing the flexibility and strength needed for expansion and sealing of piping systems and processing equipment operating at elevated temperatures and pressures.

29.

"Bellows: Improved Structure Reduces Flex Failures", Iron Age, 172, December 24, 1953, pp 86-87.

It is claimed that a welded-diaphragm-type bellows developed for atomic energy applications offers long life under severe c litions of corrosion, vibration, and high temperature.

30.

"Bellows is Redesigned for Welding", Prod. Eng., 27, December 1956, p 161.

A change from bronze to stainless steel required thinner sections at all joints for welding.

31.

Bert, C. W., and Crites, N. A., "Experimental Mechanics in the Development of a New Miniature Pressure Transducer", Experimental Mechanics, Permagon Press, Ltd., 1963, pp 307-322.

This paper describes the development of a miniature pressure transducer of the diaphragm type, with strain elements based on a new concept. The diaphragm was only 0.0025 in. thick and 0.190 in. in diameter and it was necessary to develop a special microanalysis technique, using ultrathin brittle-lacquer coating. Special procedures were required for dilution, spraying, and curing. Consideration of the strain distribution on the diaphragm surface showed that the optimum arrangement had radial strain elements in the outer region and tangential ones in the central portion. A unitized etched-foil design was developed in which all four arms of the bridge are active arms on the diaphragm surface. The principal advantages of this design are its internal temperature compensation and its high voltage output per unit pressure change. Performance data for the transducer were gathered.

32.

Berwald, W. B., Buss, H. A., and Reistle, C. E. Jr., "Bureau of Mines Multiple-Diaphragm Recording Subsurface-Pressure Gage", Bureau of Mines Rept. of Investigations 3291, November 1935, 19 pp.

Accurate measurement of subsurface pressures and temperatures in producing oil and gas wells is an important step to place the practice of petroleum production on an exact scientific basis. This report presents briefly the part of the Bureau of Mines has played in the development of suitable instruments for these measurements and gives in detail, largely through drawings, the design, construction, and operation of a new recording subsurface pressure gage, utilizing a series of thin, tempered-steel diaphragms, which has been used by Bureau engineers.

33.

Bhuta, P. C., "Analysis of Toroidal Shells of Semi-elliptical Cross Section Subjected to a Uniform Internal Pressure", M. S. Thesis, Pennsylvania State University, 1957.

The purpose of this study is to perform the stress analysis of toroidal shells of semi-elliptical cross section. The shell is subjected to a uniform internal pressure and the boundaries of the shell are assumed to be fixed. The analysis of toroidal shells of semi-elliptical cross section was made by G. M. Arkilic for certain types of loadings and boundary conditions; however, the solution for a shell with fixed boundaries, subjected to a uniform internal pressure alone, has not previously been given. The analysis is accomplished through the extension of the solution developed by Arkilic by using the method of asymptotic integration. The solution is valid for large values of the dimensional parameter μ. A numerical problem is solved.

34.

Black, H. L., and Lherbier, L. W., "Press Formability of Austenitic Stainless Steel", Metal Progr., June 1965, pp 62-67.

To obtain satisfactory results during press forming of austenitic stainless steels, the material should have the lowest possible yield stress and a moderate rate of work hardening. This article discusses how the composition of a stainless alloy can be modified slightly within AISI specifications to insure optimum performance.

35.

Blair, R. W., Johnson, D. L., and Morley, J. P., "Metal Bellows Seals", Lubrication Eng., 17 (10) October 1961, pp 470-475.

Sometimes temperature extremes or gamma radiation dictate the use of a metal bellows in an end-face-type seal. The purpose of this paper is to acquaint the seal designer and the seal user with the various parameters associated with the two basic types of metal bellows. Brief descriptions are given of the parameters.

36.

Borik, F., and Alers, G. A., "Measurement of the Elastic Properties of Rolled Sheet", Metallurgical Soc. of AIME, Transactions, 233 (1), January 1965, pp 7-11.

This article describes a simple measurement technique to obtain the nine elements of the elastic modulus tensor from which all the elastic properties can be deduced. Variation of Young's modulus and the rigidity modulus in the principal planes of ausformed steel sheet is discussed.

37.

Botosan, R. A., and Sorensen, A. E., "Electroforming Large Diaphragms",
Paper for presentation at the Space Power and Propulsion Symposium,
Philadelphia, June 3-5, 1963.

The successful use of vacuum-formed plastic molds as mandrels for electro-
forming of large parts has not been previously reported. Three advantages
are associated with the manufacturing process: (1) the wood molds required
for the manufacture of the mandrels are inexpensive and may be quickly made
by any pattern shop, (2) the plastic mandrels are inexpensive and may be
produced at a high rate, and (3) three-dimensional objects having back
angles may be manufactured in one piece.

38.

Boyd, W. K., and White, E. L., "Compatibility of Rocket Propellants With
Materials of Construction", Battelle Memorial Institute DMIC Memorandum 65,
September 15, 1960.

This report summarizes the available information on the compatibility of
liquid rocket propellants with prominent materials of construction. Compati-
bility data for materials not ordinarily covered by the Defense Metals Informa-
tion Center are included. These data were found during the search for in-
formation on materials that are within the scope of the DMIC, and are included
for convenience. Fuels and oxidizers of current interest are discussed.
The corrosion data which are presented apply to storing, handling, and con-
trol equipment outside of missiles and to missile components up to the
combustion chamber. The compatibility of materials with reaction products
in combustion chambers, nozzles, etc., has not been considered.

39.

Boyd, W. K., Berry, W. E., and White, E. L., "Compatibility of Materials
With Rocket Propellants and Oxidizers", Battelle Memorial Institute DMIC
Memorandum 201, January 29, 1965.

This memorandum summarizes compatibility data on ammonia, boron-fuels,
halogen oxidizers, hydrazines, hydrogen, hydrogen peroxide, methylene
chloride, nitric acids, N_2O_4, oxygen ozone and solid propellants.

40.

Brombacher, W. G., and Lashof, T. W., "Bibliography and Index on Dynamic
Pressure Measurements", Natl. Bur. of Standards Circ. 558, February 14, 1955.

This bibliography and index is one of a series of reports intended to sum-
marize the state of the art in various areas of the field of instrumentation.
The circular contains 850 items on dynamic pressure measurement and related
subjects such as static pressure measurement and general information on the
components of instruments. An index of the bibliography by both subject
and author is included.

41.

Brombacher, W. G., "Bibliography and Index on Vacuum and Low Pressure Measurement". Natl. Bur. of Standards Monograph 35, November 10, 1961.

This bibliography and index on vacuum and low pressure was prepared for scientists, engineers, and others. The bibliography contains 1538 references, of which 52 are on books. About 550 of the periodical references are specifically on pressure measurement, including both vacuum gages and micromanometers. The balance are on vacuum technology, including adsorption, degassing, vacuum pumps, controlled gas leaks, valves, seals and vacuum systems, all of which bear on the technique of vacuum measurement. The indices consist of an author index and an index of the subject matter of the listed references.

42.

Brombacher, W. G., Goerke, V. H., and Cordero, F., "Sensitive Aneroid Diaphragm Capsule With No Deflection Above a Selected Pressure", J. of Res., Natl. Bur. of Standards, 24, January, 1940, pp 31-32.

A sensitive diaphragm capsule has been designed in which the two corrugated diaphragms nest into each other at external air pressures above a desired value. Evacuated capsules of this type have particular application in measuring pressure with radio sondes of the Diamond-Hinman-Dunmore type, where the deflection of the contact arm is fixed. At the ground level the diaphragms are designed to nest into each other and deflection does not begin until the air pressure is reduced to the value called the cut-off pressure. Several elements of two capsules each were constructed with a cut-off pressure of 140 millibars. When installed in a radio sonde in place of the usual type, which is responsive over the entire range of pressures, a sevenfold increase in sensitivity in pressure measurement was obtained at altitudes above 46,000 ft.

43.

Brombacher, W. G., "Some Problems in the Precise Measurement of Pressure", Instruments, 22, April 1949, pp 355-358.

Engineering and scientific literature reveals a steady stream of articles on new or improved instruments for measuring pressure. Broadly speaking, this field may be held to include both indicating and recording instruments, remote indicating instruments, pressure regulators and controllers. Measurements may be made dynamically or statically. Only indicating instruments primarily for static use are discussed in this article, although the discussion may have application to other fields.

44.

Brower, D. F., "What You Can Do With Magnetic Pulse Forming", Metal Prog., 87 (4), April 1965, pp 79-83.

Magnetic pulse forming is used in many assembly operations in the automotive, aircraft, and aerospace, electrical and process industries. Typical applications include joining of power transmission torque tubes to end fittings,

"shrink" fitting of difficult assemblies, and the compression of preformed rotating bands onto artillery shells.

45.
Brown, W. F., Jr., and Thompson, F. C., "Strength and Failure Characteristics of Metal Membranes in Circular Bulging", ASME Trans., 71, 1949, pp 575-585.

Circular hydraulic bulges were formed from a group of materials having widely varying strain-hardening rates. The complete development of the shapes and strain distributions was determined experimentally, and the stress and radius of curvature at the pole were calculated as a function of the maximum strain. An analysis of the data revealed that strain gradients and, therefore, the bulge heights were influenced by the stress-strain characteristics of the metal. It was also found that the bulge contour was closely approximated by a sphere only at strains in the vicinity of the instability strain. Instability was exhibited by all materials having a sufficient ductility at strains varying from $\epsilon = -0.47$ for annealed 7075 aluminum to $\epsilon = -0.64$ for annealed low-carbon steel.

46.
Brown, W. F., Jr., and Sachs, G., "Strength and Failure Characteristics of Thin Circular Membranes", ASME Trans., 70, April 1948, pp 241-251.

The problem treated in this paper concerns the deformation and failure characteristics of thin circular metal membranes. The instability phenomena encountered in the deformation of such shapes is analyzed in terms of strain distribution and also by previously developed equations relating the stress-strain and radius-strain functions. The paper also develops the fact that the circular bulge test appears particularly suitable for determining basic stress-strain relations to much higher strain values than are obtainable by conventional methods.

47.
Budiansky, B., and Radkowski, P. P., "Numerical Analysis of Unsymmetrical Bending of Shells of Revolution", AIAA Journal, 1 (8), August 1963, pp 1833-1842.

A general numerical procedure, based on the linear theory of Sanders, is developed for the elastic stress and deflection analysis of a shell of revolution subjected to arbitrary loads and temperatures. The shell may have variable and discontinuous, but axisymmetric, geometrical and mechanical properties. The procedure involves the expansion of all pertinent load, stress, and deformation variables into Fourier series in the circumferential direction; the individual Fourier components of stress and deflection then are found separately by matrix solution of the finite-difference forms of appropriate differential equations in the meridional coordinate.

48.

Bulgakov, V. N., Statics of Toroidal Shells, Kiev. Akad. Nauk Ukr SSR, 1962 (In Russian).

This is an extensive monograph on the analysis of toroidal shells. After the development of the theory of shells of rotation and of toroidal shells, the author discusses numerical methods of solving the problems. The two methods discussed are the Runge-Kutta integration and the finite difference approach. Tables of influence coefficients for torus shells are presented and a number of examples are calculated.

49.

Bulgakov, V. N., "Application of Numerical Methods to the Calculation of a Toroidal Shell", Trudy Konf. po Teorii Plastin i Obolochek, Kazan', 1960, pp 4-45 (in Russian).

This is one of the earliest Russian papers on the numerical solution of toroidal shells. Both Runge-Kutta integration and finite-difference approaches are discussed. No numerical results are given but the author states that two toroidal shells were solved by the Runge-Kutta approach on the computing machine, "Strella", which coincided with the solutions given by Clark.

50.

Bulgakov, V. N., "Calculation of Torus-Shaped Bellows for Axial Load and Internal Pressure", Sb. Trudov La. Gidravl. Mash., Kiev, Izd. AN UkSSR (9) 1961, pp 94-102. (In Russian)

A computer program had been written earlier for the calculation of stresses in shells of revolution using the finite difference approach. This program was used to calculate stresses in seven omega joint bellows.

51.

Bulgakov, V. N., and Karpenko, I. V., "Numerical Solutions of a Homogeneous Equation of a Toroidal Shell", Sb. Trudov Lab. Gidravl. Mash., Kiev, AN UkSSR (9), 1961, pp 89-93 (in Russian).

This paper discusses the application of the Runge-Kutta technique to the numerical integration of the equations for a general shell of revolution. A computer program written for the Russian machine "Strella" was used to solve two toroidal shell problems and the results are compared with Clark's analytical solutions.

52.

Bulgakov, V. N., "A Toroidal Shell Under the Effect of Centrifugal Forces", Prikl. Mekh., 3 (2), 1957 (in Ukranian).

This paper deals with an examination of the calculation of a rapidly rotating toroidal shell filled with a fluid. V. Novozhilov's complex theory of thin

shells is utilized. The principal equation is deduced for the toroidal shell at a given loading. The solution of the homogeneous equation is given in the form proposed by Zenova - Novozhilov. The partial solution of the nonhomogeneous equation is found by the method of variation of arbitrary constants. The special functions entering into the solution are tabulated. The effect of boundary conditions upon the stresses in the toroidal shell is considered.

53.

Burry, P. E., "The use of a Nonuniform Diaphragm for the Reduction of Acceleration Errors in a Pressure Transducer", Tech. Memo No. T.D. 37, Royal Aircraft Establishment, Farnborough, September 1958 (AD 207266).

Several types of pressure transducers now available or under development use integrally machined diaphragms. It is shown that by reducing the thickness of the outer portion of the diaphragm and increasing that of the central portion, a reduced sensitivity to acceleration may be obtained while retaining the original pressure sensitivity.

54.

Campbell, J. E., "Review of Current Data on the Tensile Properties of Metals at Very Low Temperatures", Battelle Memorial Institute DMIC Rept. 148, February 14, 1961.

In reviewing the current data on the tensile properties of metals to liquid-hydrogen temperature (-423 F), some results may be summarized as follows: (1) face-centered cubic metals, some cobalt alloys, some magnesium alloys, some titanium alloys, tantalum, and zirconium tend to retain considerable ductility at very low temperatures; (2) to minimize brittle fracture tendencies at very low temperatures, special precautions should be taken in design and fabrication to avoid stress concentrations in equipment for low-temperature use, and (3) qualification of welding or joining techniques for equipment to be used at very low temperatures can be accomplished only by testing appropriate specimens at the service temperatures. Specific recommendations are given for a variety of metals.

55.

Cardullo, M. W., "Metal Expulsion Diaphragm Development for Spherical Pro-pellant Tanks", Minneapolis-Honeywell Aeronautical Divn., December 12, 1962 (N63-19991).

This report describes the design and development of an 18-inch metal expulsion diaphragm for spherical propellant tanks. Ten of the convoluted diaphragms were tested with water. Units evaluated were of 0.010 and 0.015 inch thickness. Tests conducted on both sizes indicated that over 90 percent of the volume above the diaphragm would be expelled with a differential pressure

of less than 4 psi. However, expulsion efficiency over 98 percent required upward of 25 psi. Results of this program indicate that the fabrication method evolved would be applicable to a wide range of diaphragm sizes.

56.
Carey, R., "Welded Diaphragm Metal Bellows", Electromechanical Components and Systems Design, 7 (8), August 1963, pp 22-25.

Welded-diaphragm metal bellows consist of metal contours, called diaphragms, welded in series at the inside edge to form convolutions. A series of convolutions are stacked and welded at the OD to form a capsule. The fittings are then attached to the capsule to form the final assembly. A few typical applications of welded-diaphragm metal bellows together with the advantages for each application are described in the article.

57.
Carey, R. M., "Eight Applications for Metal Bellows", Prod. Eng., 33 (24), November 26, 1962, pp 58-59.

Brief descriptions are given of metal bellows used as precision couplings, fluid accumulators, shaft seals, and pressure actuators.

58.
Carter, B. C., et al., "Measurement of Surface Strains in Diaphragms", Engineering, 168, December 2, 1949, pp 581-583.

In the employment of metal diaphragms in pressure gauges it is almost invariably the practice to measure the central deflection of the plate. This method has good sensitivity with moderate pressures, up to, say, 100 lb per sq in. As the maximum pressure is increased, however, the plate thickness needs to be greater in relation to the diameter and the maximum deflection decreases unless the diameter is increased sufficiently. The permissible diameter being limited, special methods are described for use at high pressures to measure deflections with sufficient accuracy to obtain pressure measurements correct to within ±1 percent.

59.
Casacci, S. X., and Picollier, G., "A Study of the Bending of Constant-Thickness Toroidal Shells Under Axisymmetrical Loading", Houille Blanche (17), pp 14-38, January, February, 1962 (in French).

The analytical study of the axisymmetrical bending of toroidal shells is always highly complex, even if only small elastic strains are considered. For certain loading cases, approximate analytical solutions can be found in

the form of a linear combination of two Hankel functions of order 1/3. The particular solutions for other loading cases are either expressed by means of a Fourier series, the coefficients of which are calculated by means of continuous fractions (V. V. Novoshilov), or by combining simple functions and a Lommel function (R. A. Clark). In the method described, the basic equations are transformed into a Fredholm integral equation system, analytical solutions of which can be obtained with the aid of asymptotic expressions. The authors restrict themselves to an examination of a numerical solution, which is applied to the calculation of stresses and strains in a toroidal bellows element undergoing axial loading.

60.

Cassidy, L. M., and McGrattan, R. J., "Computer Techniques for Stress Analysis of Reactor Vessels", Nucl. Congress Paper No. 57, 1962.

The authors attempt, in this paper, to demonstrate the facility with which certain stress analysis problems associated with reactor pressure vessels can be solved through the use of high-speed computers. Some of the solutions and methods outlined have been previously presented and are further discussed; others are believed unique to the authors. The analyses presented have been programmed for the IBM 704 digital computer.

61.

Chapman, M., and Kirk, C. R., "A Survey of Some Fast-Responding Pressure Transducers", Royal Aircraft Establishment, Farnborough, England, I.R. 15, November 1962 (AD 410886).

Descriptions are given of various types of transducers, including some which use the movement of diaphragms to vary the electrical resistance between electrodes.

62.

Chandler, W. L., "Bellows in the Refrigeration Industry", Refrigerating Eng., 42, Part I, pp 297-299, November 1941; Part II, pp 381-387, December 1941.

Brief design formulas are given for determining the spring rate, pressure resistance, and effective area of a bellows. The use of two-ply bellows and the estimate of fatigue life are discussed briefly.

63.

Chernina, V. S., "Calculation of a Tubular Compensator for Extension and Bending", Energomashinostroenie, 8, 1959 (in Russian).

The asymptotic solution for toroidal shells given by V. V. Novozhilov is used to calculate the stresses in an omega joint under axial tension and bending of the attached pipe, and the results are compared with experimental data.

64.

Chernina, V. S., "Calculation of Toroidal Shells", Izv. AN SSSR, OTN, Mekh. i Mash., 4, pp 116-123, 1961 (in Russian).

The author obtains series solutions for two shell problems involving toroidal shells of unusual shapes. The first problem involves a torus for which the torus radius is larger than the distance from the axis of revolution to the center of the torus so that the shell intersects the axis of revolution. The second problem is concerned with the other extreme for which the torus radius is small and the distance from the axis to the center of the torus is very large.

65.

Chernina, V. S., "On the System of Differential Equations of Equilibrium of Shells of Revolution Under Bending Loads", Prikl. Mat. Mekh., 23, pp 258-265, 1959 (translation).

When the nonaxisymmetric loads of a shell of revolution are represented in terms of a Fourier series in the circumferential angle, the differential equations can be reduced to an eighth order system of ordinary differential equations. This paper shows how this system can be partially integrated to obtain a fourth order system if the loads depend on only the sine cosine of the angle.

66.

Chernina, V. S., "The Stressed State of a Special Type of Convoluted Bellows", Energomashinostroienie, 7, 1961 (in Russian).

The asymptotic solution for the deformation of a toroidal shell is used to calculate stresses in a semitoroidal bellows, and the results are compared with some experimental measurements on one bellows.

67.

Chernina, V. S., "The Stressed State of a Toroidal Shell of Medium Thickness", Izv. AN SSSR, OTN, Mekh. i Mash., 3, pp 96-104, 1959 (in Russian).

This paper considers the deformation of toroidal shells of medium thickness, by expanding the shell equations in powers of the ratio of thickness to local curvature in the manner of Reissner. The curves are given comparing the stresses obtained by the linear theory of thin shells and a theory including second-order thickness corrections.

68.

Chernina, V. S., "The Stressed State of a Tubular Compensator Operating Under Bending Conditions", Inzh. sb., 22, 1955, pp 133-149 (in Russian).

This paper considers a toroidal bellows under bending loads. The solution is obtained using the asymptotic theory of Novozhilov. Calculations are made for one toroidal bellows and compared with some experimental data.

69.

Chernina, K. P., "On the Membrane Theory of Shells", In Investigations on Elasticity and Plasticity, No. 3, Leningrad Univ., 1964, pp 3-23 (in Russian).

The author of this paper attempts to develop criteria for determining when the membrane theory of shells is applicable. Some examples are discussed.

70.

Chernykh, K. P., The Linear Theory of Shells, II, Leningrad State Univ., 1962 (in Russian).

This is the second of two volumes on the linear theory of shells. In addition to a discussion of many aspects of shell theory, this volume includes a discussion of the toroidal shell, torus-shaped bellows, and semitoroidal bellows. A solution is obtained for these shells using Novozhilov's asymptotic approach.

71.

Chernykh, K. P., and Shamina, V. A., "Calculation of Toroidal Shells, I", Investigations on Elasticity and Plasticity, 2, Sb. (3) of the Leningrad Univ., 1963, pp 247-346 (in Russian).

This is an extensive survey article on the state of the art of the theory of toroidal shells through 1962. Many of the landmark theories for toroidal shells are presented and discussed, including Stange's, Dahl's, Clark's, and Novozhilov's. A number of the papers on formed bellows of various types are discussed. The references are a valuable cross section of the Russian literature in the field through 1962. Some use of numerical approaches by Bulgakov in Russia is noted.

72.

Chi, Sun Hwan, "Bibliography and Tabulation of Damping Properties of Nonmetallic Materials", Univ. of Minnesota, WADD-TR-60-540, September 1962.

This bibliography was compiled as an aid for those people interested in damping research and related fields. It contains a nearly complete list of references on the damping properties of nonmetallic materials for the period from 1929 to 1959, together with an index of nomenclature, units, and test methods. Tabulations of the in-phase and out-of-phase components of Young's modulus and the shear modulus for the various materials are also shown.

73.

Chizhov, V. F., "Stability of Corrugated Cylindrical Shells Loaded by External Pressure", Izv. Vuish Uchebn. Zaved. Mash., 3, 1964, pp 35-46 (in Russian).

This paper considers the buckling of bellows under external pressure. The approach used is to consider the bellows as a cylindrical shell with reduced effective rigidity equal to that of the bellows. The effective rigidity is calculated from the corrugation shape using energy methods. Buckling loads for a number of bellows were calculated and compared with experiments. The experimental critical loads were from 60 to 90 percent of the calculated loads.

74.

Clark, R. A., "Asymptotic Integration in Shell Theory With Applications to Toroidal-Shell Expansion Joints", Contract No. DA-33-019-ORD-1996, October 15, 1955, through October 14, 1956.

A method of asymptotic integration of a nonhomogeneous differential equation containing a large parameter, developed in a previous report, is applied to the differential equations of the theory of thin elastic shells of revolution. A particular problem of a toroidal-shell expansion joint subject to an axial load is considered. Based on the assumption that a certain parameter is large, explicit expressions for the maximum bending stress, maximum direct stress, and axial deflection are obtained for a shell of arbitrary radial cross section and varying thickness.

75.

Clark, R. A., "Asymptotic Solutions of Toroidal Shell Problems", Quart. Appl. Math., 16, April 1958, pp 47-59.

A few years ago a method of asymptotic integration was developed by E. Reissner and the author for a nonhomogeneous differential equation involved in certain problems of the theory of thin elastic toroidal shells. Using this method, solutions were found for the problem of bending in a curved tube (considered as a sector of a shell of revolution) and for the mathematically similar problem of a toroidal expansion joint subject to an axial force. The purpose of this paper is to indicate how the method used before can be refined and how the approximate solutions previously obtained for these problems can be generalized and extended. Higher-order terms or corrections of two different types are obtained for toroidal shells of circular cross section and uniform thickness. Some of the results are found by specializing solutions derived first for toroidal shells of arbitrary cross section and possibly varying thickness, assuming only that the shell has a plane of symmetry perpendicular to the axis of revolution.

76.

Clark, R. A., and Reissner, E., "Deformations and Stresses in Bourdon Tubes", J. Appl. Phys., 21, December 1950, pp 1340-1341.

The state of stress and deformation in the tube may be considered as a superposition of two states: (1) stresses and deformations in a complete

torus subject to wall pressure; (2) stresses and deformations in an incomplete torus acted upon by bending moments at the ends. State 1 is treated as a problem in the theory of axisymmetrical deformations of thin shells of revolution. State 2 is treated in the same manner after introduction into the theory of a nonaxisymmetrical component of circumferential displacement.

77.

Clark, R. A., "On the Theory of Thin Elastic Toroidal Shells", J. Math. Phys., 29, October 1950, pp 146-178.

In this paper, toroidal or ring shell problems are considered from the point of view of the small deflection theory of thin shells of revolution loaded symmetrically with respect to their axis. Solutions of such problems are found by applying methods of asymptotic integration of a differential equation involving a large parameter multiplied by a function which vanishes at certain points. As examples of the general procedure developed the particular problems of an "Omega" piping expansion joint subject to axial load and of a corrugated pipe subject to axial load or internal pressure are solved. In particular, explicit formulas are given for the maximum stresses and displacements in terms of the dimensions of the shells.

78.

Clark, R. A., and Reissner, E., "A Problem of Finite Bending of Toroidal Shells", Quart. Appl. Math., 10, January, 1952, pp 321-334.

This paper is concerned with a nonlinear problem involving finite axisymmetrical deflections of toroidal shells with circular cross section. The problem is that of an expansion joint for two straight sections of a cylindrical shell loaded in an axial direction. The particular kind of expansion joint investigated is generally called an "Omega" joint.

79.

Clark, R. A., Gilroy, T. I., and Reissner, E., "Stresses and Deformations of Toroidal Shells of Elliptical Cross Section", J. Appl. Mech., 19, March 1952, pp 37-48.

This paper is concerned with the application of the theory of thin shells to several problems for toroidal shells with elliptical cross section. These problems are as follows: (a) closed shell subjected to uniform normal wall pressure, (b) open shell subjected to end bending moments, (c) combination of the results for the first and second problems in such a way as to obtain results for the stresses and deformations in Bourdon tubes. In all three problems the distribution of stresses is axially symmetric but only in the first problem are the displacements axially symmetric. The magnitude of stresses and deformations for given loads depends in all three problems on the magnitude of two parameters.

80.

Cohen, G. A., "Computer Analysis of Asymmetrical Deformation of Orthotropic Shells of Revolution", AIAA J., 2 (5), May 1964, pp 932-934.

Finite-difference methods of digital computer solution of the field equations for elastic shells of revolution have been described previously for iso-tropic shells subject to sinusoidal loads and for orthotropic shells sub-ject to axisymmetric loads. In the present paper the method of forward inte-gration is developed for the more general case of orthotropic shells sub-ject to sinusoidal loads.

81.

A Compendium of the Properties of Materials at Low Temperature (Phase 1), Part 1, "Properties of Fluids", WADD Tech. Rept. 60-56, Natl. Bur. of Standards Cryogenic Eng. Lab., July 1960.

This first phase of the Compendium covers ten properties of 10 fluids (Part 1), three properties of solids (Part 2), and an extensive bibliography of references (Part 3). Density, expansivity, thermal conductivity, specific heat and enthalpy, transition heats, phase equilibria, dielectric constants, adsorption, and surface tension and viscosity for the solid, liquid and gas phases of helium, hydrogen, and neon, nitrogen, oxygen, air, carbon monoxide, fluorine, argon, and methane are given wherever adequate data could be collected. Thermal expansion, thermal conductivity, and specific heat and enthalpy are given for a number of solids of interest in cryogenic engineering. Data sheets, primarily in graphic form, are presented from "best values" of data collected. The source of the material used, other references and tables of selected values with appropriate comments are furnished with each data sheet to document the data presented. Conversion tables and other helpful informa-tion are also included.

82.

Cook, W. P., "Stresses in Seal Welds", Knolls Atomic Power Lab. Rept. No. KAPL-M-WPC-1, July 20, 1957.

The solution for stresses induced in seal welds by displacements and pressure forces is shown. The results are in the form of curves from which stresses may be calculated.

83.

Cooper, R. M., and Shifrin, G. A., "An Experiment on Circular Plates in the Plastic Range", Proc. of the Second U. S. Natl. Congress for Applied Mechanics, ASME, 1954, pp 527-534.

Nine simply supported mild-steel circular plates were loaded well into the plastic range under concentric, uniformly distributed loads. Deflection, strain and slope data were obtained as functions of load. Comparison is made with the predicted limit loads of Hopkins and Prager.

23

84.

Cope, E. T., and Wert, E. A., "Load-Deflection Relations for Large Plain, Corrugated, and Creased Pipe Bends", Trans. of ASME, FSP-54-12, 1954.

This paper presents the results of tests made on 10-in. and 14-in. seamless steel pipe loaded in the same manner as the simple cases shown on pages 526 to 529, "Piping Handbook", by Walker and Crocker. Comparison is made between calculated deflections and the results of tests in the six cases for a plain pipe bend. The relation between the results of tests on corrugated and creased pipe bends and the calculated results for plain pipe bends of the same dimensions are shown. Such calculations are included as are necessary to show the method of analysis by which the load-deflection relations of a plain quarter-bend and its tangents are determined.

85.

Cordero, F., et al., "A Nonlinear Instrument Diaphragm", J. of Research, Natl. Bur. of Standards, 58 (6), June 1957, pp 333-337.

Details of fabrication for the production of sensitive diaphragms having a controlled nonlinear pressure-deflection characteristic are presented. The desired characteristic was such that when the diaphragm formed one plate of a condenser in the frequency-controlling network of a Wien-bridge oscillator, the resulting pressure-frequency transfer characteristic would be linear between -30 and +30 dynes per square centimeter. Typical transfer curves are shown.

86.

Crites, N. A., "For Stress Analysis - Brittle-Coating Methods", Prod. Eng., 32 (42), November 27, 1961, pp 63-72.

Second in a series on stress-analysis techniques, this article describes how to select coatings, prepare and analyze crack patterns, and discusses a new micro technique.

87.

Crites, N. A., "Your Guide to Today's Strain Gages", Prod. Eng., 33 (4), February 19, 1962, pp 69-81.

Third in a series on stress-analysis techniques, this article discusses the popular types and methods for installation and protection.

88.

Crites, N. A., Grover, H. J., and Hunter, A. R., "Experimental Stress Analysis by Photoelastic Techniques", Prod. Eng., 33 (18), September 3, 1962, pp 57-69.

Fifth in a series on stress-analysis techniques, this article gives information on equipment, materials, model calibrations, and stress interpretations.

89.

Cumming, E. P., "Thirteen Ways to Use Metallic Bellows", Prod. Eng., 23 (6), June 1952, pp 162-163.

Sketches show typical and unique applications of metal bellows, and ways of transferring motion to other elements.

90.

Cushing, F. S., Chreitzberg, A. M., "Research and Development on Cells With Bellows Controlled Electrolyte Levels", Electric Storage Battery Co. First Quart. Rept., June 10 to September 10, 1964 (N64-33918).

Preliminary Cd/KOH/NiOOH cell tests have verified that bellows action in a sealed cell can be used to flood the plates under low pressure conditions to maximize discharge capacity and to drain the plates under high pressure overcharge conditions to aid in gas recombination. Metallic and nonmetallic bellows were considered. Plastic pillows, partially inflated with air, and sealed within the cell, are proposed as bellows substitutes. The pillow $\Delta V/V$ value is approximately twice the present metallic bellows volume efficiency.

91.

Dahl, N. C., "Toroidal-Shell Expansion Joints", J. Appl. Mech., 20, (4), December 1953, pp 497-503.

In the problem considered in this paper a thin toroidal shell of center-line radius α and torus midsurface radius b, slit at its inner edge and welded to relatively stiff cylindrical pipe sections to form an expansion joint. Stresses and axial deformation under the axial load P are calculated. A solution is obtained using the principle of minimum complementary strain energy. It is found that the results obtained in this way are valid as long as μ is not too large. This solution is plotted together with the asymptotic solution obtained by Clark to show in what regions of μ the solutions overlap, and both solutions are compared with experimentally determined stresses and deformations.

92.

Daniels, C. M., "Designing for Duct Flexibility With Bellows Joints", Machine Design, 31 (21), October 1959, pp 146-155.

In ducting systems, bellows offer flexibility to absorb thermal expansion and contraction, installation misalignment, structure deflection, and vibration. This article presents a review of the factors that influence their selection and application. It is based upon the design of aircraft and missile fuel systems where ducts run the gamut of extreme temperatures, pressure, and flow velocity.

93.

Daniels, C. M., "Pressure Losses in Flexible Metal Tubing", Prod. Eng.,
April 1956, pp 223, 225, 227.

Friction coefficients and pressure loss data are given for corrugated flexible
hose of annular and helical types at high flow rates (Reynolds Number 2×10^6).

94.

Daniels, C. M., and Fenton, R. E., "Pressure Loss Factors for Internally
Linked Bellows Joints", Machine Design, 33 (19), September 14, 1961, pp 187-189.

This article presents experimentally determined loss factors for fluid flow
in two types of internally linked bellows joints: the chain-link type, and
the gimbal-ring type.

95.

Danilova, I. N., "Calculation of Toroidal Bellows Under the Effect of Axial
Tensile Strength During Creep of the Material", Izv. Akad. Nauk SSSR, OTN,
10, 1958 (in Russian).

This paper considers an omega joint undergoing creep under axial loading.
A method of solution is sketched for an exponential creep law.

96.

DeCrescente, M., and Janz, G. J., "Brass Bellows Gauge for Null-Reading
Manometers", Rev. Sci. Instr., 28 (6), p 468, June 1957.

This note describes a mechanical gauge made from commercially available
components and requiring a minimum of machining and glass blowing. The
gauge is capable of accuracy at room and elevated temperatures comparable
to that of the mercury manometer-cathetometer assembly.

97.

Delmonte, J., "A Versatile Miniature Flush-Diaphragm Pressure Transducer",
ISA Proc., 7, pp 174-177, 1952.

A variable-resistance, unbonded strain-gage type of electrical pressure gage
is described that is basically 1/2-inch in diameter by 5/8-inch in thickness,
and weighs about 20 grams. The gage was designed to measure pressure
fluctuating at high frequencies as well as measuring steady-state pressures
with errors of less than one percent of full scale. The gage has been tem-
perature compensated over the range of plus 165 deg. to minus 65 deg. F, and
its output is convenient to drive recording galvanometers directly.

98.

Deneff, G. V., "Fatigue Prediction Study", Douglas Aircraft Co. Report WADD TR 61-153, January, 1962.

Fatigue life prediction of complex structure is investigated from the standpoint of fundamental factors that influence the prediction; namely, stress, fatigue strength, and damage method. Stresses developed by a general stress-analysis procedure are combined with appropriate fatigue-strength data to estimate the fatigue strength of a structural joint. Factors influencing the joint fatigue strength under spectrum conditions are analyzed and a method of estimating this fatigue strength is presented. Damage methods utilizing several types of fatigue-strength data are considered. The influence of geometric factors on the fatigue strength of basic material is also studied and presented in a normalized form.

99.

Dickinson, T. A., "Problem: To Make These Bellows" Welding Eng., 39 (10), pp 47-53, October 1954.

A brief description is given of resistance-welding equipment developed for making thin, stainless steel bellows.

100.

Dolginov, L. S., "Calculation of Steam Pipes With Convoluted Bellows Without Tie Rods", Sudostroyeniye, 4, 1959 (in Russian).

This paper considers the use of bellows as motion compensators in a piping system with offset pipes. A method is given for considering bellows without tie rods. This permits considering any part of the steam line taking into account the flexibility of the bellows both in axial compression and in bending. A successive-approximation technique is used to obtain the solution for a given problem. One numerical example is given.

101.

Donkle, L. B., "How to Avoid (Corrugated) Metal-Hose Failure", Prod. Eng., 31 (30), pp 43-48, July 25, 1960.

Metal hose in high-pressure, high-temperature, flexing applications can last a hundred years - or fail in minutes. The author discusses causes of failure, and tells how to overcome them.

102.

Donnell, L. H., "The Flexibility of Corrugated Pipes Under Longitudinal Forces and Bending", ASME Trans., 54, pp 69-75, 1932.

Pipes with circumferential corrugations are used in expansion bends in steam lines and in other applications where longitudinal or bending flexibility

is required. In this paper the longitudinal flexibility is calculated for several types of corrugations, and from this a "reduced modulus of elasticity" is derived by which corrugated pipes can be calculated as if they were smooth. A set of experiments is described which check these results.

103.
Douglas Aircraft Co., Missile and Space Systems Division, Test Rept., "Bellows, Duct, Oxidizer Tank Vent Qualification", January 24, 1964 (AD 443333).

Tests of a 3-3/4-inch-diameter bellows included compression spring rate, proof pressure (44 psig), leak (bubble), deflection-pressure (44 psig at -300 F), life cycling (50 deflections), pressure cycling (200 cycles 0-29 psig), and burst.

104.
Douglas Aircraft Co., Test Rept., "Qualification, Bellows, Fuel Tank Vent - External", December 9, 1964, IDEP 115.56.69.00-D7-09.

Tests of a 6-inch-diameter bellows included proof pressure (64 psig), leakage (bubble), spring rate, pressure cycling (200 cycles), ambient deflection cycling (50 cycles), life cycling (200 cycles), and burst (1900 psig).

105.
Douglas Aircraft Co., Test Rept., "Qualification, Bellows, Tee, Fuel Tank Vent", December 9, 1964, IDEP 115.56.69.00.D7-08.

Tests of a 4-inch-diameter bellows included proof pressure (47 psig), leakage (bubble), spring rate, pressure cycling (200 cycles), ambient deflection cycling (50 cycles), cold deflection cycling (150 cycles at -374 F), life cycling (2000 cycles), and burst (1500 psig).

106.
Douglas Aircraft Co., Missile and Space Systems Divn., Test Rept., "Qualification, Bellows, Duct, Oxidizer Tank Vent", December 9, 1964, IDEP 115.56.69.00-T7-07.

Tests of a 5-inch-diameter bellows included proof pressure (44 psig), leakage (bubble), spring rate, pressure cycling (200 cycles), deflection cycling (50 cycles), cold deflection cycling (150 cycles at -300 F), life cycling (200 cycles), and burst (925 psig).

107.

Douglas Aircraft Co., Missile and Space Systems Divn., Test Rept., "Qualification, Bellows, Propulsive Fuel Vent", September 15, 1964, IDEP 115.56.69.00-D7-05.

Tests of a 6-inch-diameter bellows included proof pressure (46 psig), leakage (bubble), spring rate, pressure cycling, deflection cycling (50 cycles), cold deflection cycling (150 cycles at -350 F), and burst (1900 psig).

108.

Douglas Aircraft Co., Missile and Space Systems Divn., Test Report, "Design Development, Positive Expulsion System, Auxiliary Propulsion System", August 3, 1964, IDEP 115.56.69.00-D7-04.

Tests of 6 welded bellows included leakage (bubble), deflection cycling (10 cycles), proof pressure (45 psig), vibration, life cycling (1000 cycles), and spring rate.

109.

Douglas Aircraft Co. Test Rept., "Qualification, Bellows, LOX Tank Fill & Drain Line, Fuel Tank", December 9, 1964, IDEP No. 115.16.79.00-D7-02.

Tests of a 4-1/2-inch-diameter bellows included proof pressure (160 psig), leakage (bubble), spring rate, pressure cycling, (200 cycles), ambient deflection cycling (50 cycles), cold deflection cycling (150 cycles), life cycling (150 cycles), and burst (750 psig).

110.

Douglas Aircraft Co., Test Rept., "Qualification, Bellows, LOX Tank Fill & Drain Line", December 9, 1964, IDEP No.115.16.79.00-D7-01.

Tests of a 5-1/2-inch-diameter bellows included proof pressure (215 psig), leakage (bubble), spring rate, pressure cycling (200 cycles), ambient deflection cycling (50 cycles), cold deflection cycling (150 cycles at -320 F), life cycling, and burst (1900 psig).

111.

Douglas Aircraft Co., Test Rept., "Qualification, Bellows, LOX Tank Fill & Drain Line", December 9, 1964, IDEP 115.16.69.00-D7-03.

Tests of a 4-1/2-inch-diameter bellows included proof pressure (110 psig), leakage (bubble), spring rate, pressure cycling (200 cycles), ambient deflection cycling (50 cycles), cold deflection cycling (150 cycles at -320 F), life cycling (150 cycles), and burst (3000 psig),

112.

Douglas Aircraft Co., Test Rept., "Bellows, Hydrogen Vent, Internal, Quali-
fication Test", July 22, 1964 (AD 454341).

Tests of a 6-inch bellows included proof pressure (17 psig), leakage (bubble),
spring rate, deflection cycling (1000 cycles), pressure cycling (1000
cycles at -320 F), and burst.

113.

Douglas Aircraft Co., Missile & Space Systems Divn., Test Rept., "Bellows
Assembly, Relief, Fuel Tank Qualification Test", July 27, 1964 (AD 454320).

Tests of a 1/2-inch-diameter bellows included spring rate, proof pressure
(64 psig), leakage (helium), deflection cycling (50 cycles), pressure cycling
(0 - 42 psig, 200 cycles at 345 F), and burst pressure.

114.

Douglas Aircraft Co., Missile & Space Systems Divn., Tech. Memo., "Expansion
Joint, GH_2 Engine Vent, D/E", November 26, 1962 (AD 416867).

A description is given of tests to evaluate two universal bellows expansion
joints for providing flexibility for an engine. The tests include proof pressure
(60 psig), leakage (bubble), pressure cycling (200 and 500 cycles to 15 psig),
deflection cycling (50 and 200 cycles), and surge (100 psig).

115.

Douglas Aircraft Co., Missiles & Space Systems Divn., Tech. Memo., "Oxidizer
Fill Line, Flexible Bellows", November 11, 1962 (AD 401998).

The oxidizer fill line assembly transfers liquid oxygen from the ground
supply tank into the vehicle oxidizer tank. The system includes a flexible
metal bellows which is located within the vehicle oxidizer tank. Tests were
conducted to evaluate the bellows under simulated service conditions. The
tests included proof pressure (80 psig), leakage (bubble), pressure cycling
(0 to 49, 200 cycles), and deflection cycling (25 cycles at 49 psig).

116.

Douglas Aircraft Co., Missile & Space Systems Divn., Test Rept., "Design
Evaluation/Qualification Test of Internal Metal Flexible Bellows", January
8, 1963, IDEP 115.16.69.00-D7-02.

Tests of a 3-inch-diameter bellows included proof pressure (80 psig, GH_2),
leakage (54 psig, GH_2), pressure cycling (200 cycles, 0 to 49 psig LN_2)
and deflection cycling (25 cycles, pressurized with LN_2).

117.

Douglas Aircraft Co., Missile & Space Systems Divn., Test Rept., "Quick Disconnect, LH$_2$ Engine Vent System", October 29, 1962, IDEP 115.56.69.00-D7-01.

Tests of two stainless steel and one aluminum bellows conducted to evaluate the design of a disconnect assembly under flight conditions included spring rate, leakage (-250 F, 11 psig), disconnect (3 times, -250 F, 11 psig), and vibration.

118.

Draper, C. S., "A New High-Performance Engine Indicator of the Strain-Gage Type", J. Aeron. Sci., 16 (10), pp 593-610, October 1949.

This paper describes a new pressure receiver using a high-flexibility catenary-type diaphragm and a temperature-compensating wire-wound strain gage designed for satisfactory pressure-measuring characteristics with greatly reduced response to temperature and extraneous mechanical effects.

119.

Dressler, R. F., "Bending and Stretching of Corrugated Diaphragms" (J. Basic Eng.) ASME Trans., 81, pp 651-659, December 1959.

Solutions of the exact linear elastic-shell equations for all stresses and displacements are presented for a typical corrugated-diaphragm shape for three thicknesses varying over a 9 to 1 range. Results were obtained by numerical integration using an electronic digital computer. The effect of thickness-diameter-ratio variation is discussed with respect to both stresses and resultants, and peak values needed for design purposes are presented. Circumferential and meridional stresses are found to be equally important throughout the thickness range analyzed. Bending and membrane stresses are likewise equally important throughout the range. Peak values in some cases occur near the outer rim.

120.

Drucker, D. C., and Hopkins, H. G., "Combined Concentrated and Distributed Load on Ideally Plastic Circular Plates", Proc. of Second U.S. Natl. Congress for Appl. Mech., ASME, pp 517-520, 1954.

This paper has two main objectives: to extend the work on circular plates to the experimentally realizable cases of large or small overhang, and to demonstrate that answers may be obtained in a straightforward manner for any yield condition and almost any radially symmetric loading. As an example, the Tresca yield criterion is assumed and the collapse condition is calculated for an overhanging circular plate subjected to both a central force and a uniformly distributed pressure within the support circle. Solutions for the simply supported and for the built-in plate appear as special cases.

121.

Drucker, D. C., and Shield, R. T., "Limit Analysis of Symmetrically Loaded Thin Shells of Revolution", J. Appl. Mech., 26, pp 61-68, March 1959.

The yield surface for a thin cylindrical shell is shown to be a very good approximation to the yield surface for any symmetrically loaded thin shell of revolution. Hexagonal prism approximations to this yield surface, appropriate for pressure vessel analysis, are described and discussed in terms of limit analysis. Procedures suitable for finding upper and lower bounds on the limit pressure for the complete vessel are developed and evaluated. They are applied for illustration to a portion of a toroidal zone or knuckle held rigidly at the two bounding planes. The combined end force and moment which can be carried by an unflanged cylinder also is discussed.

122.

Drucker, D. C., "Plastic Design Methods - Advantages and Limitations", Office of Naval Research Tech. Rept. No. 24, Brown Univ., July 1957.

Assembly and welding stresses add to the stress imposed by loading, and it is inevitable that stress concentrations will produce some local plastic flow in the best of designs. An exact plastic design would be a formidable task, but neglecting work-hardening provides a simple and yet a reasonably satisfactory approximation termed limit design. At the limit load the idealized structure collapses. For the overwhelming majority of structural problems, a design based upon a reasonable factor of safety against this plastic collapse provides a more appropriate structure than a design based upon elastic action. Although limit analysis is relevant, a more complete analysis is needed for plastic buckling, strengthening by secondary membrane stresses, and brittle fracture. Illustrations are provided.

123.

Dubinskiy, S. A., Rusanova, Ye I., Stol, B. F., "Calculation of Toroidal Bellows of a Low-Pressure Pipeline", Sudostr., 5, pp 14-16, 1956 (in Russian).

The asymptotic solution is found by the method of Novozhilov for some omega bellows with either clamped or simply supported edges. The results are compared with experiments.

124.

"Electron Beam Welds Pay Off for Bellows Maker", Steel, 148, pp 78-79, March 6, 1961.

This article describes the use of electron-beam welding as an alternative to tungsten-arc welding in the manufacture of welded bellows for use in pressure sensors.

125.

Ellis, A. H., and Howard, J. H., "What to Consider When Selecting a Metallic Bellows", Prod. Eng., 21 (7), pp 86-89, July 1950.

Brief descriptions are given of the design, fabrication, life, and use of metallic bellows. A life-prediction chart is included.

126.

"An Engineering Evaluation of Methods for Prediction of Fatigue Life in Airframe Structures", Lockheed-California Co., March, 1962 (AD 276249).

From a study of twenty proposed fatigue-life-prediction methods, ten of the procedures were chosen for evaluation numerically with a group of 78 complex spectral test results representing approximately 266 individual specimens. An experimental program generated constant amplitude axial load S-N type data on simple notched coupons of 7076-T6 aluminum alloy sheet for use in the analysis procedures. Ordered spectral fatigue test data from these same type coupons were utilized from another concurrent ASD fatigue research program. A series of specimens of a complex joint were also fatigue tested. These data were analyzed by the selected procedures to confirm or provide a possible means of improving the selected fatigue-life-prediction methods.

127.

Engl, W., "How to Determine the 'Effective Area' of a Disk Diaphragm", Regelungstechnisch Praxis (Munich), 7 (5), pp 165-168, May 1959 (in German).

One side of a disc diaphragm is loaded by a pressure which is opposed by a force acting upon the other side of the disc. As a result, the diaphragm is deflected in the direction of the greater pressure. This article shows a method of calculating, for small deflections, the "effective area", that is, the area from which, by multiplying it with the pressure, the opposing force can be found. A device is described consisting mainly of a very stiff pressure transducer which at the same time produces and measures the opposing force.

128.

Ericson, G. L., Boyd, W. K., and Miller, P. D., "Corrosion of Titanium and Titanium-Base Alloys in Liquid and Gaseous Fluorine", Titanium Met. Lab., TML Memo., April 30, 1958.

Unalloyed titanium and four titanium-base alloys were subjected to a simple preliminary corrosion evaluation in liquid and gaseous fluorine at temperatures between -320 F and +220 F. All materials exhibit promising corrosion resistance under the test conditions. More elaborate experiments would be desirable to fully establish the utility of titanium in fluorine service.

129.

Estabrook, L. H.; and Jahsman, W. E., "Stress Analysis of Welded Bellows",
General Electric Tech. Information Series (DF56 SL 219), May 28, 1956.

The general solution for welded bellows given in KAPL-1089 was applied to
a bellows loaded by radial edge forces and edge moments at its ends. Equa-
tions for deflections, rotations, forces, moments, and stresses throughout
the bellows were developed using matrix algebra. The limitations of the anal-
ysis were investigated. Numerical results were obtained for an 8-inch stop
valve bellows using an IBM 650 digital computer. The analysis is quite general
and may be applied to any welded bellows of similar geometry. The complete
solution for additional loading conditions, such as axial and pressure loads,
may be obtained by superposition. Matrix algebra was used, so the resulting
equations are in convenient form for solution on a digital computer. High
stresses were found at the point of a small applied radial displacement at
the lower end of an 8-inch stop-valve bellows which is free at its upper
end. For this case, the solution became unstable after 3 convolution pairs
from the lower end. This instability is probably due to: (a) numerical
errors arising from taking small differences of large numbers and/or (b)
application of the solution to a bellows configuration which exceeds the limi-
tations of the theory. To resolve this problem, further study was
recommended.

130.

Estrin, M. I., "One Method for the Solution of a Homogeneous Problem
for a Symmetrically Loaded Toroidal Shell", Prikl. Mat. Mekh., 17, pp 619-622,
September/October, 1953 (in Russian).

This paper gives a minor variation of Novozhilov's asymptotic solution for
toroidal shells.

131.

Exline, P. G., "Pressure Responsive Elements", ASME Trans., 60 (8), pp 625-
632, November, 1938.

Pressure-responsive elements commonly used in indicating and recording instru-
ments are manometers, free-piston gages, Bourdon tubes, diaphragms, and
bellows. The mathematics of the primary elements, manometers, and free-
piston gages is simple and direct. Analyses of Bourdon tubes and diaphragms
show that predictions of their performance curves are not amenable to precise
calculation even under the simplest conditions, which conditions do not
generally obtain in instruments. Generally, the instrument maker must rely
upon empirical knowledge, coupled with approximate calculations, for design
data. Linkage adjustments must be provided to correct for variations in
dimensions and materials normally encountered in manufacture. Emphasis is
placed on the usefulness of bellows as pressure elements, and approximate
formulas for calculating their behavior are given. The results of considerable
experimental work on the characteristics of bellows of various sizes and
materials show that in many cases they are ideal elements for pressure-
responsive instruments. An example of such use in a special-duty pressure
gage is given.

132.

Famili, J., and Archer, R. R., "Finite Asymmetric Deformation of Shallow Spherical Shells", AIAA J., 3 (3), pp 506-510, March 1965.

A procedure is developed for the integration of the system of nonlinear partial differential equations governing the asymmetric deformation of shallow spherical shells. A suitable iteration scheme based on a finite-difference approach is shown to yield the asymmetric post-buckling states for the spherical cap under uniform pressure. Thus, the practically important asymmetric "lower buckling load" is systematically computed for the first time. Applications to more general asymmetric buckling problems are indicated by the example of the spherical cap with the load distributed uniformly over half of the surface.

133.

Farrar, J.F.P., "Development of Metal Bellows in Germany During War Years Through 1946", FIAT Final Rept. 1076 (PB 78651), March 1947.

A short report is given of the developments in the manufacture of metal bellows in Germany during the war through 1946; brass bellows of good quality were manufactured, but much more slowly than is common in the United States; however, no developments in the industry purportedly took place during the war and production methods as compared to those in the United States is antiquated.

134.

Farrell, M. J., "The Development of Advanced Cryogenic Pressure Switches for Ballistic Missiles", Frebank Co., June 1960 (AD 243423).

A low-pressure-switch program has resulted in the development of an advanced cryogenic pressure switch which functions with two diaphragms essentially the same as the medium pressure switch described in Volume 1 of this report. The low-pressure switch has demonstrated that it is capable of withstanding the severe environmental conditions encountered in ballistic missile usage by passing the Qualification and Flight Rating Testing which included combined environmental testing.

135.

Favor, R. J., et al., "Investigation of Fatigue Behavior of Certain Alloys in the Temperature Range Room Temperature to -423 F", Battelle Memorial Institute, June 1961 (AD 266343).

The fatigue behavior of certain alloys has been investigated in the temperature range room temperature to -423 F. The alloys evaluated were materials currently used for components in cryogenic missile systems. The results of an initial literature search are presented graphically as S-N curves and as fatigue strength-temperature cross plots. In the experimental program, equipment was designed to test small sheet specimens in fully reversed bending, constant maximum deflection experiments at temperatures down to -423 F. Detailed descriptions of the equipment and specimens are presented. Fatigue data obtained on 14 alloys at room temperature, -110 F, -320 F, and

-423 F are presented graphically. The metallurgical histories and chemical analyses are described.

136.

Feely, F. J., Jr., and Goryl, W. M., "Stress Studies on Piping Expansion Bellows", J. Appl. Mech., 17, pp 135-141, 1950.

As a result of numerous and costly failures of the stainless steel bellows used to take up thermal expansion in the piping of petroleum and chemical processing equipment, a bases has been developed for designing these bellows to operate within reasonable stresses. A formula has been derived to show the total stress induced in the material as a result of the combined effects of pressure and movement. The validity of the approximations used in this formula has been verified by laboratory strain-gage measurements on an experimental bellows. A relationship between several variables in the design of the disks has also been determined and serves as a basis for dimensioning them to achieve the most economical proportions. When this relationship is satisfied, the maximum permissible movement per disk can be obtained. This is shown graphically. Several supplementary formulas are given for determining bellows characteristics which may affect the design of adjacent piping. The problem of designing an expansion joint for high-pressure service is discussed briefly, and some preliminary laboratory data are presented on a commercial joint of this type.

137.

Filippov, A. P., and Bulgakov, V. N., "Application of Quick-Response Computers to the Investigation of the Strength of Plates and Shells", Prikl. Mekh., 7 (2), pp 125-134 1961 (in Russian).

This paper describes the way a computer may be used to solve problems in plates and shells. As examples, a toroidal shell is solved by finite differences, and a curved plate is solved by energy methods and the integral-equation approach.

138.

Finnie, I., "An Experimental Study of Multiaxial Creep in Tubes", 1963 Joint Intern. Conf. on Creep, Sect. 2, New York, pp 21-26, August, 1963.

The different methods available for the prediction of creep rates under multiaxial stress are discussed and it is pointed out that the best experimental studies in the literature lead to apparently contradictory conclusions. Tests on tubes of aluminum and lead were made under torsion, internal pressure and tension in an attempt to resolve this difficulty, but none of the methods of strain prediction in the literature adequately explained the results. This discrepancy is attributed to the effect of hydrostatic stress which has hitherto been assumed negligible in creep strain predictions. It is suggested, based on the known mechanisms of plastic deformation in metals, that the equations used for strain prediction may have to be modified when the temperature exceeds about half the melting point in degrees absolute. On this basis many of the apparent contradictions in the literature may be resolved.

139.
Fitzgibbon, D. P., "Experimental Measurements of the Stiffness of a Pressurized Bellows System", Space Technology Laboratories Rept. No. EM 8-20, October 1, 1958.

The stiffness of a pressurized convoluted bellows is dependent not only on the structural stiffness but also on the pressure stiffness of the bellows. The pressure stiffness arises because the resultants of the pressure forces acting on the deflected bellows produce a moment which is proportional to deflection. It was recognized that these two contributions to the stiffness of a bellows could be balanced against each other to reduce the magnitude of the moment required to deflect the bellows. Subsequently, a theoretical analysis was made in which the stiffness of a bellows system was found as a function of applied pressure and pivot point location. This analysis (Seide, P., "The Effect of Pressure on the Bending Characteristics of an Actuator System", ASME Trans., 82, 1960, AD 605937) predicts that points of zero stiffness can be obtained over a range of pressures for various pivot point locations. The investigation reported herein is the experimental evaluation of that theory.

140.
Fleming, L., "Research on Transducers for Extreme Environmental Temperatures", Bell & Howell Research Center, Pasadena, Calif.

The problem of utilizing a high-temperature deflection sensing element in a pressure or acceleration transducer is chiefly one of finding and fabricating materials for springs and diaphragms which have good elastic properties at elevated temperatures. Studies made at Gulton Industries have concluded that no metal is available which has adequately low elastic hysteresis and creep above 1000 F. Structural nonmetallics such as beryllia and high-alumina ceramics show, however, considerable promise.

141.
Flindt, C. B., "Theory of Restrained Corrugated Diaphragms", Engineer (London) 202 (5246) pp 193-195, August 1956.

The corrugated metal diaphragm has been used for many years as the basis of measuring instruments, in which the force due to fluid pressure is balanced by stresses set up in the metal as it deflects. Many theoretical studies have been published which seek to explain the behaviour of such diaphragms, but only those dealing with linear deflections have been very successful. In this article the theory of linear diaphragms, originally due to J. A. Haringx, is developed with the purpose of calculating the thrust which can be exerted by a restrained diaphragm under uniform pressure conditions.

142.
Flügge, W., and Steele, C. R., "Toroidal Shells With Nonsymmetric Loading", October 1, 1959 (AD 229108).

The problem of a general shell of revolution, without geometric discontinuities, under slowly varying edge loading has been solved for dome-shaped shells and

for nonshallow shells but not for the toroid -- distinctive because of the interaction between "bending" and "membrane" effects. The eighth-order partial differential equations for a shell of revolution reduce for sinusoidal edge loading to an eighth-order ordinary differential system - three simultaneous equations. These proved unwieldy for the toroid and so were reduced in this work to one nonhomogeneous integral-differential equation which can be further modified to a form quite similar, except for the integral, to a fourth-order formulation of the axially symmetric problem treated previously. With this formulation, the complete solution for a toroid with edge loading of a given harmonic requires the numerical solution of two simple equations, equivalent to equations of the first order, a considerable amount of straightforward numerical integration, and, for the most general boundary conditions, the solution of 8 simultaneous algebraic equations. Although this could be tedious by hand, particularly for several harmonics, it would be routine for a digital computer.

143.

Forrest, P. G., _Fatigue of Metals_, Pergamon Press, Long Island City, 1962.

About half the book is devoted to the fatigue strength of metals and the influence of such factors as metallurgical structure, stress concentrations, surface treatment, corrosion, and temperature. In addition, fatigue testing techniques and the fatigue strengths of joints, components, and structures are treated in some detail. There are also sections on engineering design to prevent fatigue failure.

144.

Frederick, C. O., "Model Correlations for Investigating Creep Deformation and Stress Relaxation in Structures", J. Mech. Eng. Sci., 7 (1) pp 57-66, 1965.

This paper establishes a range of possible creep model correlations based on uniaxial constant-stress-creep data and variable stress creep laws. It is shown that the model behaves as an analogue which can be used to solve the differential equations governing the deformation of the prototype. The most general correlations hold for time-hardening materials where creep data can be fitted by a stress index. The least general correlations hold for strain-hardening materials whose data can only be fitted to a function of stress. Elastic strains and variable loads are included in the analysis.

145.

Galletly, G. D., "A Comparison of Methods for Analyzing Bending Effects in Toroidal Shells", ASME Trans., 80, pp 413-414, September 1958.

An accurate estimate of the effects of bending loads acting on toroidal shells is, at the present time, a time-consuming problem for the designer. He is, in consequence, interested in the accuracy with which the faster approximate methods can furnish him with the information he requires. The

author had occasion to utilize two approximate methods in the bending analysis of a toroidal shell of revolution as well as an exact method. The purpose of this note is to present the results of these analyses insofar as they pertain to the calculation of the edge displacements and rotations.

146.

Galletly, G. D., "Edge Influence Coefficients for Toroidal Shells of Positive Gaussian Curvature", ASME Trans., 82 (1), pp 60-68, February 1960.

Tables are given for the edge deformations of constant-thickness toroidal shells subject to uniform pressure and edge bending loads. Over 100 different shell geometries were investigated and the results are presented in dimensionless form. Possession of these coefficients, which were obtained on a digital computer, means that a rapid and accurate formulation of the compatibility equations at toroidal shell-junctions is possible.

147.

Galletly, G. D., "Edge Influence Coefficients for Toroidal Shells of Negative Gaussian Curvature" (J. Eng. Ind.) ASME Trans., 82 (1) pp 69-75, February 1960.

Continuing the work presented previously, the present paper gives additional tables for the edge deformations of constant-thickness toroidal shells subject to edge bending loads and uniform pressure. The two papers together thus cover a wide variety of toroidal-shell geometries and enable a designer to calculate in a simple manner the edge moments and shears at toroidal-shell junctions.

148.

Galletly, G. D., "On Particular Integrals for Toroidal Shells Subjected to Uniform Internal Pressure", ASME Trans., 80, pp 412-413, September 1958.

For toroidal shells which do not include the apex $\phi = 0$, two common approximations are used to evaluate a particular integral of the relevant differential equations. These approximations, which are known to violate the compatibility relations and are chosen to satisfy only the equilibrium conditions, are: (a) the transverse shear Q_ϕ and the rotation V are both set equal to zero, and the stress resultants N_ϕ and $N\theta$ are given by their membrane values. (b) Same as (a), except that the rotation V is given by the membrane rotation V_m. The purpose of the present note is to point out that these approximations are not very good even when ϕ is as large as 30 degrees. To illustrate the point, a constant-thickness toroidal shell under uniform internal pressure is investigated.

149.

Galletly, G. D., and Radok, J.R.M., "On the Accuracy of Some Shell Solutions", ASME Trans., 81, pp 577-583, December 1959.

R. B. Dingle's method for finding asymptotic solutions of ordinary differential equations of a type such as occur in the bending theory of thin shells

of revolution is presented in outline. This method leads to the same results as R. E. Langer's method used for problems of this kind, and permits a simple analytical and less formal interpretation of the asymptotic treatment of such equations. A comparison is given of edge influence coefficients due to bending loads, obtained by use of these asymptotic solutions and numerical integration of the equilibrium equations, respectively. The particular shells investigated are of the open-crown, ellipsoidal, and negative-curvature toroidal types. The results indicate that the agreement between these solutions is satisfactory. In the presence of uniform pressure, the use of the membrane solutions for the determination of the particular integrals appears to lead to acceptable results in the case of ellipsoidal shells. However, in the case of toroidal shells, the membrane and the numerical solutions disagree significantly.

150.

Gartner, D., Kromrey, H., "New Process for Production of Single-Wall Metal Bellows by Chromizing and Their Testing", Technik, 17, pp 72-73, February 1962 (in German).

Formed bellows are used as packing elements. The special advantages of this type of sealing are complete tightness, absence of maintenance and of gland friction. The disadvantages of single-wall formed bellows used as sealing elements are their low life and the limits of permissible work pressure. The usual materials for metal-formed bellows are tombac, yellow brass, stainless steel (18/8-CrNi), etc... In the new method of the VEB Measuring Instrument and Armature Plant "Karl Marx" of Magdeburg, the formed bellows are of ferrite steel developed by chromium plating steel 5 Ti 5.

151.

General Dynamics/Astronautics Test Rept., "Design Proof Test Report for Bellows Assembly - Life Chill-down Manifold", June 20, 1963. IDEP 115.12.69.00-D5-01.

Tests of two bellows assemblies included proof pressure (15 psig for 5 min. with LN_2), vibration (at -300 F) and life cycling (10 psig ~ 500 cycles, displaced 2°).

152.

General Dynamics/Astronautics, Test Rept., "Hose Assembly--Vernier, Liquid Oxygen Supply, MA-3", January 18, 1962 (AD 288344).

Tests of 15 flexible-metal hose specimens included initial performance tests (750 and 1500 psig, H_2O), vibration, acceleration, life cycling (12,000 cycles), and burst (3000 psig).

153.

General Dynamics/Astronautics Test Rept., "Report of Preproduction Tests of Bellows Assembly", November 25, 1959. IDEP 115.10.60.00-D5-01.

Tests of two concentric bellows included leakage (at 18 psig), proof pressure (42 psig), deflection cycling (1000 cycles at -300 F), and burst pressure (70 psig).

154.

General Dynamics/Astronautics Test Rept., "DPT Report for Hose, Metal-Fuel Bleed-Engine Control", October 10, 1962 (AD 296609).

Tests of a braid-covered 3-inch-diameter bellows included visual examination, pressure deflection (250 psig, 100 in-lb), life cycling (200 cycles), proof pressure (500 psig LH_2) and burst (1410 psig).

155.

General Dynamics/Astronautics Test Rept., "Acceptance Test of Fittings, 0 - 100 psig", August 22, 1961 (AD 276304).

Acceptance tests are described of a flexible elbow, flexible line, special line, transfer line, and elbow. The tests included visual examination, proof pressure (150 psi), and two types of leak tests.

156.

Gerberich, W. W., Martin, C. F., and Zackay, V. F., "Serrated Stress-Curves of Metastable Austenite in Alloy Steels", Am. Soc. for Metals Trans., 58 (1), pp 85-94, March 1965.

The macroscopic yield behavior of metastable austenite in nine alloy steels was studied. It was found that the degree of austenite decomposition was directly proportional to the amount of strain.

157.

Geschelin, J., "How Metal Bellows are Fabricated by the Cook Electric Co.", Automotive and Aviation Industries, 92, pp 36-38, February 15, 1945.

Manufacturing facilities are extremely flexible, providing with few exceptions a job-shop type of operation capable of handling a vast variety of parts and assemblies in any quantity from one to hundreds of thousands. Assembly processes embody practically every known method of welding and brazing or soldering.

158.

Gibbs, D. F., "Spring Diaphragms", J. Sci. Instr., 34, pp 34-35, January 1957.

A brief description is given of diaphragms convoluted in various ways.

159.

Gleyzel, A., "Plastic Deformation of a Circular Diaphragm under Pressure", J. Appl. Mech., 15, pp 288-296, 1948.

In this report a numerical solution is given of a set of equations consisting essentially of three plasticity laws, two strain-displacement laws, and two equilibrium laws which describe the action of a clamped, thin, circular diaphragm

as it yields plastically when pressure is applied to one side. The stresses, strains, thickness variation, and deflections for any thin circular diaphragm of a given material may be computed by the numerical integration of the equilibrium conditions, the geometric conditions relating displacements and strains, and the stress-strain laws. The solution may be reduced to the solution of a second-order differential equation with the radial distance r as independent variable. The solution depends upon an experimentally determined function $\tau(\gamma)$, which describes the stress-strain properties of the material, and upon three parameters, the presure p, the original thickness h_o, and radius a of the clamping ring. It is found that for a given material, a family of curves with pa/h_o as a parameter serves to predict the solution for any thin circular diaphragm of the same material. This analysis has been carried out for a particular function $\tau(\gamma)$ based upon results of tensile tests made on a specimen of medium steel. Graphs of theoretically and experimentally determined values of deflection, radial and circumferential strains, radial and circumferential stresses, and thickness corresponding to various pressures are presented which apply to all diaphragms made of the same steel as this specimen.

160.

Gohn, G. R., "Fatigue of Metals: Part 1, The Mechanism of Fatigue", Mater. Res. and Stands., 3 (2), pp 106-115, February 1963.

This is the first of three companion articles on all facets of fatigue. Part 1 reviews all of the theories of fatigue crack initiation accompanied by 44 references. Early fatigue failures are examined. This vast background of effort points to the fatigue model of Wood as the current, most plausible discussion of the mechanism of fatigue. This model recognizes the microstructure and assumes that the dislocation theory is valid. Attention is confined to small plastic strains ±ε alternating about a zero mean stress. This type of fatigue need not result in strain hardening below a certain strain amplitude, called "reversible plastic set". The deformation process changes (under cycling) from coarse to fine slip in the crystal as the strain amplitude becomes less than the reversible plastic set; and fatigue deformation accompanies fine slip bands or course slip bands consisting of an avalanche of fine slip bands. This explains how fatigue develops at some intensified slip band; it accounts for the formation of notch-like contours at certain bands; it accounts for the tendency of the slip to concentrate in the bands first formed, and the numerous observations that show fatigue usually deteriorates the surface.

161.

Goldberg, J. E., Bogdanoff, J. L., "Static and Dynamic Analysis of Nonuniform Conical Shells Under Symmetrical and Unsymmetrical Conditions", Ballistic Missile and Aerospace Technolog., Academic Press, New York, pp 19-238, August 1961.

The equations for determining stresses and displacements in symmetrically and unsymmetrically loaded thin conical shells are presented in a form which is especially convenient for numerical integration on an electronic digital computer. The usual assumptions of classical shell theory are employed. Thickness and mechanical properties of the shells may vary along the generators and temperature distributions which do not produce significant circumferential variation of mechanical properties may be handled. Results obtained for several problems of symmetrical and unsymmetrical vibration are displayed.

162.

Goldberg, M. A., and Pifko, A. B., "Large Deflection Analysis of Uniformly Loaded Annular Membranes", AIAA J., 1 (9), pp 2111-2115, September 1963.

An iterative technique is employed to obtain approximate solutions to Foppl's nonlinear membrane equations. Four uniformly loaded rotationally symmetric membranes are examined: (a) an annulus fixed at both edges, (b) an annulus fixed at the outer edge with a rigid plug in the interior, (c) an annulus fixed at the outer edge and free of tractions at the inner edge, and (d) a solid circular membrane fixed at the outer edge. Numerical results are presented for each problem. The results of case (d) are compared with the existing exact power-series solution presented by Hencky. Stresses and deflections computed by the iterative technique for case (d) are within 1.14 percent of those predicted by Hencky.

163.

Grafton, P. E., and Strome, D. R., "Analysis of Axisymmetrical Shells by the Direct Stiffness Method", AIAA J., 1 (10), p 2342, October 1963.

A method for the structural analysis of shells of revolution, composed of materials with orthotropic properties, is discussed. The development is based on the direct-stiffness method. A truncated cone element is introduced to take advantage of symmetry. Derivations of the stiffness and stress matrices for the truncated cone element are given. Several examples are solved on the digital computing machine using a program that is based on the truncated cone element. The results are compared to other theoretical results, and the correlation is excellent. Extension of the technique to handle linear unsymmetric deformation and nonlinear symmetric deformation is discussed.

164.

Greenbaum, G. A., "Comments on 'Numerical Analysis of Unsymmetrical Bending of Shells of Revolution'", AIAA J., 2 (3), pp 590-592, March 1964.

This note comments on the paper by Radkowski, et al., on the finite difference solution of shells of revolution. The note gives conditions appropriate for shells closed at the apex. This permits the solution to be obtained at the axis without the necessity of leaving a small hole on the axis.

165.

Grigger, J. C., and Miller, H. C., "The Compatibility of Materials With Chlorine Trifluoride, Perchloryl-Fluoride, and Mixtures of These", Pennsalt Chemicals Corp., April 1961.

Compatibility and corrosion rates of alloys of aluminum, copper, magnesium, nickel, titanium, steel and stainless steel, and columbium, molybdenum, carbon,

graphite and fluorocarbon plastics in chlorine trifluoride, perchloryl fluoride and mixtures of these at 30 C were investigated. Titanium, columbium, molybdenum, carbon and graphite were rapidly attacked in ClF₃. Corrosion rates of others were extremely low in all liquids. In the vapors, instances of higher corrosion rates were noted. Teflon and Kel-F adsorbed moderate amounts of ClF₃ and ClO₃F. Passivation by ClF₃ was unnecessary for reducing corrosion of properly cleaned metals. Corrosion in wet ClO₃F was characterized by localized attack, but some stainless steels were resistant. Titanium exhibited increasing impact ignition in liquid ClO₃F beginning at 19 ft-lb, but even at 140 ft-lb burning was not sustained. No other metals showed impact ignition in ClF₃ or ClO₃F. In explosive shock tests, ClO₃F gave a stronger interaction with the metals tested than did ClF₃ and aluminum showed a greater interaction with the fluorine chemicals than low carbon or stainless steel. Greatest enhancement of explosive shock occurred with titanium and ClO₃F. In explosive denting and perforation of steel and aluminum cylinders containing ClF₃, ClO₃F and their mixtures, no enhancement occurred. A high order explosive interaction occurred between ClO₃F and titanium cylinders perforated by a shaped explosive charge.

166.

Grigoryev, B. V., "Some Problems in Flanging and Beading Membranes", NASA Tech. Transl. F-32, 13 pp, June 1960.

The hydraulic method of beading may be used equally well for membranes of cold-worked materials and for materials which have undergone thermal treatment, to give them high yield strength. The method of flanging and beading membranes which is under consideration gives considerably more stable properties and less residual deformations, elastic fatigue, and hysteresis than membranes prepared by means of resin, lead, or steel stamps and dies.

167.

Grinstad, C. E., Frawley, R. N., et al., "An Improved Indicator for Measuring Static and Dynamic Pressure", SAE J. (Trans.), 52 (11) pp 534-555, 1944.

The principle of operation and the mechanical design of an improved indicator for measuring static and dynamic pressures are discussed in this paper. The condenser type of indicator was selected by the authors for engine work because it is compact and sturdy, it is easily serviced, it has a high natural frequency, and it is relatively insensitive to shock and vibration. This type of indicator also does not require mechanical linkage between the pressure diaphragm and the electrically sensitive element.

168.

Grover, H. J., Gordon, S. A., and Jackson, L. R., "Fatigue of Metals and Structures", U.S. Govt. Printing Office, 1954 (currently being revised).

This book is directed particularly to the designer or engineer with some knowledge of, but limited practical experience, in fatigue problems. It is intended to provide a summary of present-day information and to provide

references to published literature for more complete information on the most important items in such design. It is recognized that in a number of instances present-day knowledge is incomplete, hence the information presented is considered as a guide and a starting point toward adequate solution of specific problems.

169.

Grover, H. J., and Bell, J. C., "Some Evaluations of Stresses in Aneroid Capsules", Proc. of Soc. Exptl. Stress Anal., 5, pp 125-131, 1948.

Two lines of attack were followed: first, experimental evidence of surface stress distribution was obtained by the use of brittle-lacquer coatings on several capsules subjected to various loading conditions; second, a mathematical computation of stresses in a model, quite similar to common aneroid capsules was carried out to give numerical results. The primary purpose of the investigation was to study drift and mechanical hysteresis in aneroid capsules and to develop methods of producing capsules with less drift and hysteresis. This involved the consideration of many factors, including the choice of material for diaphragms; optimum heat treatment, aging, and cold working of diaphragm materials; fabrication of diaphragms; methods of joining diaphragms to produce capsules; and effects of variation in design of capsules. Previously, attention had been mainly directed to the conventional corrugated diaphragm type of capsule and to commonly used materials such as beryllium copper and phosphor bronze.

170.

Gutterman, E. P., "Diaphragms and Linkages for Pressure-Operated Flight Instruments", Office of Tech. Services, PB 134858, 225 pp, April 1956.

Pressure-sensitive, circular convoluted diaphragms experience severe biaxial stress concentrations during deflection. Resulting overstrains near the periphery and in the convolutions contribute to hysteresis and drift and limit the usable sensitive range. Some of the conclusions reached during the investigation of these configurations were: (1) a noncircular, welded, radially-convoluted, free-edge diaphragm shape can be made to reduce to zero all strains lying in the capsule surface, within the first order of approximations - only relatively evenly distributed bending strains remain; (2) free-edge diaphragm-forming dies may be shaped to satisfy the design equations by a simple, automatic computing linkage attached to a standard shaper, (3) age-hardening alloys are superior for diaphragm manufacture - raw material should be annealed dead soft before forming - since large grain-size is undesirable, a high-temperature, short-time hardening cycle should be employed; and (4) hysteresis and drift of assembled capsules may be decreased and usable range increased by artificial aging including the successive steps of deflection cycling, temperature cycling at maximum stress and moderately extended heating slightly above maximum service temperature, under maximum stress.

171.

Halford, G. R., and Morrow, J., "Low Cycle Fatigue in Torsion", Univ. of Illinois, October 1961.

Completely reversed torsional-fatigue failures are reported for two aluminum alloys, 60-40 brass and SAE 4340 steel in the life range of 1/2 to 20,000 cycles. Cyclic hysteresis loops were measured and the total plastic-strain energy to cause fracture is reported. The results are interpreted using hysteresis energy as a criterion for fatigue damage and also in terms of the Coffin equation for low cycle fatigue. Both methods of interpretation give good agreement with the test results. For practical purposes, the data are adequately described by substituting shear strains for normal strains in the Coffin equation.

172.

Hamilton, P., "The Development of Electroforming Techniques", McDonnell Aircraft Co., March 10, 1964 (AD 431518).

A test program was initiated to further develop electroforming techniques investigated under Test Request 513-277. Mandrel materials selected for evaluation were polystyrene, plexiglass (lucite), cerrotru, polyurethane, and redwood. Nickel was electrodeposited from a sulfamate electroplating bath on the prepared mandrels to the desired thickness. Completed electroformed parts were separated from their mandrels utilizing appropriate techniques. Parts successfully electroformed included a wave guide, a bellows, and a pitot tube. A sandwich structure attempted was not completed. A study form of redwood was designed and electroformed to evaluate the deposition of nickel on inside and outside corners as well as in blind holes. The internal stress produced by the nickel sulfamate bath was determined with the aid of the Brenner-Senderoff Contractometer.

173.

Haringx, J. A., "Design of Corrugated Diaphragms", ASME Trans., 79, pp 55-61, 61-62, 62-64, January 1957.

Three previous papers by the author set forth methods of calculating the rigidity of corrugated diaphragms, the stresses in the sheet material, and the nonlinearity of the relation between load and deflection. As a further step, the introduction of a few simplifying restrictions having no fundamental effect on the problem leads to the concept of a chart giving at once the dimensions a diaphragm must have so as to conform to specific requirements. An example is included by way of illustration.

174.

Haringx, J. A., "Instability of Bellows Subjected to Internal Pressure", Philips Research Repts, 7 (3), pp 189-196, June 1952.

Like thin-walled cylinders, dealt with in a previous paper, bellows also may become unstable when loaded by internal pressure. The critical value of this pressure, which in accordance with Euler's well-known formula is governed

by the rigidity of the bellows with respect to bending, has been computed only for rectangularly shaped corrugations, and has been checked experimentally.

175.

Haringx, J. A., "Nonlinearity of Corrugated Diaphragms", Appl. Sci. Res., Sect. (a), 6, pp 45-52, 1956.

Proceeding from the method of calculation for determining the rigidity of corrugated diaphragms given in a former paper, one is able to indicate what degree of nonlinearity of the relations between load and deflection is to be expected for large deformations. By means of an example it is shown that the introduction of the corrugations into the flat plate, though unavoidably increasing the initial rigidity, involves an important gain in maximum deflection for the same degree of nonlinearity.

176.

Haringx, J. A., "The Rigidity of Corrugated Diaphragms", Appl. Sci. Res., Sect. (a), 2, pp 299-325, 1950.

When the corrugated diaphragm is replaced by a fictitious flat plate of similar properties it is possible to derive a linear differential equation for the deflection. The coefficients of this equation, however, vary in a complicated way and its solution for the pressure-loaded diaphragm is only given for thick and for thin sheets separately. For thick sheets the profile of the corrugation appears to be inessential, whereas for thin sheets it is necessary to distinguish between trapezoidal, triangular and arc-shaped corrugations. By an obvious device the results for thick and for thin sheets are fitted together, so that the deflection can also be determined for the intermediate range of medium sheet thickness. The final results of the present calculation are compared with measurements carried out by others and are found to be in satisfactory agreement with the experiments. It is to be remarked that, compared on the basis of small deflections, the introduction of corrugations into the sheet leads to a considerable increase of rigidity of the diaphragm. The prevailing assertion that the flat plate is more rigid than the corrugated diaphragm holds only for large deflections, because of the nonlinearity between the load and the deflection of the flat plate.

177.

Hawthorne, R. C., "Flow in Corrugated Hose", Prod. Eng., pp 98-100, June 10, 1963.

An analytical method for calculating pressure losses is given which assumes that the corrugations behave as a series of uniformly spaced orifices and that pressure drop is caused by a succession of individual flow expansions. Test results are given.

178.

Haythornwaite, R. M., "Deflection of Plates in the Elastic-Plastic Range", Proc. of the Second U.S. Natl. Congress for Appl. Mech.; ASME, pp 521-526, 1955.

The deflections of plates with circular symmetry are computed for an elastic-plastic material that obeys the yield condition of Tresca and the associated flow rule. At any point on the plate the entire thickness is assumed to be either fully elastic or fully plastic. An annular plate simply supported at the outer radius and clamped to a centrally loaded rigid disc is analyzed in detail, the simply supported circular plate with a central concentrated load being included as a limiting case. The testing of a steel plate is described and the results obtained are compared with the theory.

179.

"High Precision Barometric Bellows", Engineering, 185, p 709, June 6, 1958.

Precision barometric bellows can be produced in any of the conventional materials used for instrument and control systems, i.e., phosphor bronze, 80-20 brass, or aluminium brass alloys; and also in Monel, cupro-nickel and stainless steel. A tolerance in spring rate as low as ±10 percent can be provided, on a production basis.

180.

Hill, R., "A Theory of the Plastic Bulging of a Metal Diaphragm by Lateral Pressure", Phil. Mag., 41, p 1133, 1950.

Explicit formulas are obtained for the stresses in a metal diaphragm which is bulged plastically by lateral pressure. The predicted influence of work-hardening on the shape of the profile, and on the relation between polar strain and curvature, agrees well with experimental data. A simple expression is developed for the instability strain.

181.

Hise, E. C., "Design, Development, and Operation of Metal-Diaphragm Reactor-Service Pumps", Oak Ridge Natl. Lab., ORNL 2841, May 10, 1960.

Aqueous homogeneous reactors require pumps capable of injecting relatively small quantities of highly radioactive, corrosive fuel solution into the high-pressure system. These pumps must have a long maintenance-free life, be absolutely leak-proof, be resistant to the radioactive and corrosive environment, and be easily replaced by remote methods when necessary. Hydraulically driven metal-diaphragm pumps capable of meeting these requirements were developed in the Homogeneous Reactor Project at ORNL. This report summarizes the development program, the operating experience with the pumps in tests and in reactor service, and the design information derived from the development program.

182.

Hoffman, J. H., et al., "Diffusion Bonding Beryllium Copper for Ultrahigh-Strength Joints", Welding J., Welding Res. Suppl., $\underline{41}$, pp 160s-166s, April, 1962.

Bond strengths averaging 108,400 psi were developed in joining precipitation-hardened beryllium-copper by diffusion techniques. This is in contrast with an average of 40,000 psi obtained by ordinary brazing techniques. The unique method of diffusion bonding studied in this program involved the use of molten alloys of silver and gold to fill discontinuities at the bond interfaces. These molten filler alloys were in turn, completely, or in some instances partially diffused into the base metals, resulting in sound and continuous base-metal-to-base-metal bonds. Joints of this type produced under high vacuum conditions, using a silver-copper-indium filler alloy, resulted in the highest bond strengths developed on this program; however, those effected in dry hydrogen atmospheres (-80 F dewpoint or better) using the same filler alloy, averaged 96,000 psi. Data were also developed on the effects of heating beryllium-copper at 1550 F and at 1475 F on grain growth, elongation, reduction in area and elastic modulus to determine its usefulness as a high-strength fabricated material for unusual applications.

183.

Hopkins, H. G., and Prager, W., "The Load Carrying Capacities of Circular Plates", J. Mech. Phys. Solids, $\underline{2}$, pp 1-13, 1953.

This paper is concerned with the load carrying capacities of circular plates made of a perfectly plastic material that obeys the yield conditions of Tresca and the associated flow rule. Various conditions of rotationally symmetric loading and support are discussed.

184.

Howard, J. H., "Designing With Metal Bellows", Machine Design, $\underline{26}$ (1), pp 37-48, 1954.

This article summarizes principles of different applications of bellows, the proper selection of bellows materials, determination of bellows proportions, basic types of bellows assemblies, and assembly methods as they influence bellows specification.

185.

Hu, W. C-L, "A Linearized Membrane Theory for Prestressed Shells of Revolution", Thesis, Stanford University, 1964.

The many new applications of expandable or inflatable structures demand a theoretical study to elucidate the mechanical behavior of an elastic shell membrane beyond the limits of the linear shell theory. The present work is directed toward the development of a theory to determine the effects of small, axisymmetric loads on an inflated shell of revolution, or, more generally, on an elastic membrane, in the form of a surface of revolution, which has been "prestressed" by a uniform inflating pressure and edge tractions.

49

186.

Hudson, G. E., "Theory of a Dynamic Elastic Deformation of a Thin Diaphragm", J. Appl. Phys., 22, pp 1-1 January 2001.

The theory presented in this article was developed in an attempt to describe the observed motion and plastic deformation of clamped metal diaphragms used in certain underwater explosion experiments and in certain mechanical gages. The approach enables one to set up certain equations of motion, which may be solved in finite form under certain conditions. The solutions enable one to specify, for instance, the final deformed diaphragm profile, the distribution of thickness after deformation, the swing-time, which is the total time for deformation to take place, and many other quantities.

187.

Hunt, L. B., "The History of Pressure-Responsive Elements", J. Sci. Inst., 21 (3), pp 37-42, March 1944.

Over one hundred years ago Lucien Vidie, a lawyer and amateur scientist of Nantes, carried out his experimental work on the measurement of atmospheric pressure by means of a closed and evacuated metallic vessel; his first patent was applied for in 1844. Much depends upon the indications of the three types of pressure-responsive elements which have been developed from this work - diaphragms, flexible bellows, and Bourdon tubes - and it is of some interest, therefore, to look back into the early history of this form of pressure measurement. For reasons connected with the elastic properties and behavior of these elements, with special reference to the materials best suited to their construction, the writer had occasion to undertake a careful search of the literature. In the course of this search there emerged a number of points of historical interest which have not apparently been recorded in any connected manner. The article outlines the general sequence of events.

188.

Hurlich, A., "Properties of Materials at Liquid-Oxygen and Liquid-Hydrogen Temperatures", General Dynamics/Astronautics, February 28-March 15, 1957.

A survey was made of the properties of materials at liquid oxygen (-293 F) and liquid hydrogen (-423 F) temperatures to assist in the selection of suitable materials for propellant tanks, bellows, and propellant lines in a satellite missile.

189.

Husen, C. F., and McClellan, R. G., "Development and Fabrication of Omni-Directional Accelerometers", Ford Motor Co., Aeronutronic Division, July 19, 1963 (N64-12170).

A description is given of a pressure transducer which is mounted so that the diaphragm is at the center of the mercury cavity. Solid-state strain

elements are bonded to the back of the pressure-sensing diaphragm and are wired in a full bridge circuit to convert the pressure-induced stress to high-voltage output. The diaphragm has a very high natural frequency which eliminates problems associated with its use as the sensing element in an accelerometer. A heavy integral flange permits installation with minimum case distortion.

190.
Hydraulically Formed Seamless Metal Bellows", Machinery (London), 74 (1893) pp 131-136, February 3, 1949.

In the process of manufacturing seamless metal bellows, a thin-walled closed-end tube is caused to flow continuously under an internal fluid pressure of several hundred pounds per sq in. in a collapsible die. The latter consists of a series of plates equal to the number of convolutions required, spaced equidistantly surrounding the tube. The internal pressure causes the metal to flow transversely between the plates as the tube collapses endwise to form the bellows in one continuous operation. No annealing is performed on the bellows after forming. A particular advantage of the process is that the amount of cold working applied to the material is under close control. This results in a very uniform grain structure and wall thickness, which is of particular importance at the curved roots and crests of the convolutions, where most of the load during flexing in service is carried, and where failure of a bellows invariably occurs.

191.
Irvine, C. N., and Barnett, J. H., "State-of-the-Art Literature Survey on Fabrication Techniques of Advanced Ducting Components", NASA Tech. Memo. X-53173, December 2, 1964.

The purpose of this state-of-the-art literature survey was to determine and define the manufacturing techniques required and the process difficulties likely to be encountered in the fabrication of elbows, bellows, and ducting assemblies for use in advanced ducting systems ranging from 2 inches to 50 inches in diameter. The report briefly covers the methods currently used in elbow, bellows, and ducting fabrication as well as some alternate methods available and new methods under development. Some information concerning the properties and fabricability of several aluminum, iron-base, nickel-base, and cobalt-base alloys suitable for use in cryogenic ducting systems is also presented. The survey indicates that advancements in the state of the art of fabricating large-diameter elbows, bellows, and ducting will be necessary for new, larger ducting system applications.

192.
Jackson, J. D., Miller, P. D., Boyd, W. K., and Fink, F. W., "A Study of the Titanium-Liquid Oxygen Pyrophoric Reaction", WADD TR 60-258, March, 1960.

A review of the literature indicates that titanium is impact sensitive under liquid oxygen below the acceptable limit for other metals. An experimental program was begun to determine the mechanism of the titanium-LOX

reaction. Several factors were investigated singly in a controlled manner using unalloyed titanium (75A) and an alloy (6Al-4V) that were carefully cleaned. The factors were: (1) exposure of a fresh surface by fracture and tearing; (2) deformation by impact using steel balls; (3). impact of smooth specially cleaned flat surfaces; (4) LOX pressure and velocity; (5) galling. The results from this program indicate that no one of the above, per se, is a primary cause of this reaction. A proposed mechanism is that heat generated by impact produces a gaseous oxygen, which is compressed at local sites. A fresh surface exposed by the impact reacts with the high-pressure gaseous oxygen. Propagation is dependent on the amount of heat generated and the rate of heat loss from the affected area.

193.

Jackson, J. D., "Corrosion in Cryogenic Liquids", Chem. Eng. Prog., 57 (4), pp 61-64, April 1961.

The large use of liquid propellants in missile systems has brought many serious problems to the missile designer and the materials engineer. One important problem is the corrosion behavior of materials of construction under the various exposure conditions of the missile and the auxiliary equipment. In the missile, short-term exposure occurs; however, the materials may be stressed almost to their yield strength. In the auxiliary equipment (such as storage tanks, pipelines, and pumps), long-term exposure, under much less severe strength requirements, occurs. This article discusses corrosion behavior and mechanical properties of metals used in handling liquid oxygen and liquid fluorine.

194.

Jackson, J. D., and Boyd, W. K., "Compatibility of Propellants 113 and 114B2 With Aerospace Structural Materials", Battelle Memorial Institute DMIC Memo 151, April 27, 1962.

Considerable interest has been generated recently in the use of two fluorinated hydrocarbons (propellants 113 and 114B2) because of their moderate boiling point and low specific heat and heat of vaporization. These compounds are being considered as propellants for vernier rockets which are used for stabilization of missiles and spacecraft. For this reason, the corrosion properties of these fluorinated hydrocarbons have been investigated with metals commonly used in missile applications. This memorandum presents the corrosion data and summarizes certain physical and chemical properties of propellants 113 and 114B2.

195.

Jackson, J. D., and Boyd, W. K., "Reactivity of Metals With Liquid and Gaseous Oxygen", Battelle Memorial Institute DMIC Memo 163, January 15, 1963.

Since the first observation of a violent reaction in early 1959, the compatibility of titanium and its alloys with liquid oxygen (LOX) has received

considerable attention. Initially, laboratory investigations were primarily limited to impact studies utilizing the ABMA impact tester or modifications thereof. Later the Air Force initiated a program to determine the mechanism of the reaction. The results of these early studies were previously summarized in DMIC Memorandum 89, dated March 6, 1961. More recently, the factors necessary to promote reactions between titanium and liquid or gaseous oxygen (GOX) have been studied under conditions similar to those which would be encountered in missile and space service. It is the purpose of this memorandum to summarize the present state of the art in the light of both past and present developments.

196.

Jackson, J. D., and Boyd, W. K., "The Compatibility of Materials in LEM Vehicle Tank With Nitrogen Tetroxide During Vibrational Impact", Battelle Memorial Institute, NAS 9-1100, January 1, 1964, to present.

The LEM oxidizer tank is to be constructed of Ti-6Al-4V, which may be impact sensitive to N_2O_4 under vibrational impact associated with lunar landing. Impact damage of the thin 40-mil sheet (stressed to 100,000 psi) was observed at about 20 in.-lb of force. No reactivity between Ti-6Al-4V and N_2O_4 was found when impacted with either 2014-T6 aluminum or Teflon for 39,000 cycles at about 6 in.-lb. No reactivity was observed in fatigue experiments where a fresh surface or chips were produced. Fatigue failure did occur after only 10^4 cycles at an impact level of about 11 in.-lb. Heat in the amount of 2 to 4 Btu/min was generated by the vibrational impact.

197.

Jaffee, R. I., et al., "Forming and Heat Treatment of Corrugated Diaphragms", ASM Trans., 41, pp 460-477, 478-479, 1949.

The amount of cold deformation resulting from forming corrugated diaphragms of beryllium-copper, 60:20:20 copper-nickel-manganese, titanium-Elinvar (Ni-Span C), and Grade A phosphor bronze was evaluated and found to consist of a small over-all elongation which was made up of larger localized elongations of 5 to 10 percent maximum reduction at the tops of corrugations and smaller localized contractions at the bottoms of corrugations. The specific effect of cold work on the age-hardening response was determined on sheet material. Tensile tests on material age-hardened in the as-received condition and with an additional cold reduction of the order of 10 percent reduction of thickness indicated that the effect of this amount of cold work was negligible insofar as the time dependence of the aging curves was concerned. The conclusion was drawn that as far as mechanical properties are concerned, a diaphragm can be heat treated according to the age-hardening curve of the unformed sheet stock without danger of overaging the most deformed sections of the diaphragm.

198.

Janssen, O., "Asymptotic Integration of the Differential Equation for a Special Case of Symmetrically Loaded Toroidal Shells", J. Math. Phys., 39 (1), pp 1-17, April 1960.

This paper deals with a special case of toroidal shells where the meridian

circles have the axis of rotation as common tangent at the origin. The small deflection theory of thin shells leads to a differential equation which is given. The purpose of this paper is to present a new and more accurate method to obtain the particular integral of equations of the same type.

199.

Jenny, C. J., "Diaphragm Device", U. S. Patent 2,162,308, June 13, 1939.

The invention relates to expansible and contractible diaphragm devices such as diaphragm devices comprising either a single flexible metal disc which will deflect when subjected to differential pressures on the sides thereof, or a pair of flexible metal discs joined together to form an expansible chamber which will expand and contract due to a preponderance of pressure on the inside or outside of said chamber. More particularly, the invention relates to the elimination of temperature errors in flexible metal diaphragms.

200.

Kaechele, L., "Review and Analysis of Cumulative-Fatigue-Damage Theories", Rand Corp., 90 pp, August 1963 (N63-21169).

An investigation of the basic concepts of cumulative damage and a comparison of several current cumulative-fatigue-damage theories are presented. It is shown that cumulative-damage theories can be categorized by determining the basic assumptions they contain regarding (1) how to properly add together the damage produced by each stress cycle, when many different cycles are mixed together, and (2) how damage progresses at one stress level. Several current cumulative-damage theories are examined and compared in terms of prediction of fatigue life under spectrum loading. The important consequence of differences in the theories considered is not different predicted lives, but rather differences in the amount of material that will provide a specified lifetime, as found by application of the theories in design.

201.

Kaechele, L., "Designing to Prevent Fatigue Failures", Rand Corp., 25 pp, February 1965 (AD 611267).

There are three main problem areas in preventing fatigue failures: prediction of the fluctuating stresses that cause fatigue, behavior of the structural material undergoing these stresses, and scatter in stresses encountered in service and in fatigue behavior. This paper concentrates on these major problem areas. The data most important for design, and some techniques for using these data, are presented and discussed. The designer's role in selecting the fatigue problems that should be studied is emphasized.

202.

Kalnins, A., "Analysis of Shells of Revolution Subjected to Symmetrical
and Nonsymmetrical Loads", ASME Trans., pp 467-476, September 1964.

The boundary-value problem of deformation of a rotationally symmetric shell
is stated in terms of a new system of first-order ordinary differential
equations which can be derived for any consistent linear-bending theory of
shells. The dependent variables contained in this system of equations are
those quantities which appear in the natural boundary conditions on a rota-
tionally symmetric edge of a shell of revolution. A numerical method of
solution which combines the advantages of both the direct integration and the
finite-difference approach is developed for the analysis of rotationally
symmetric shells. This method eliminates the loss of accuracy encountered
in the usual application of the direct-integration approach to the analysis
of shells. For the purpose of illustration, stresses and displacements of
a pressurized torus are calculated and detailed numerical results are
presented.

203.

Kaplan, Yu. I., "Calculations for Spatial (or Three-Dimensional) Construction",
Raschet Prostranstvenrakh Konstrukt., VIII, 1963 (in Russian).

This paper considers a number of problems involving toroidal shells includ-
ing toroids filled with liquid, noncircular toroids, and toroidal bellows.
Solution is obtained in trigonometric series using energy methods.

204.

Kegley, T. M., Jr., and Hammond, J. P., "Bellows Failure in Solid Separation
Loop of the HRT Mockup", ORNL Rept. CF-57-2-24, February 5, 1957.

The failure of a valve bellows appeared to be due to a combination of stress
corrosion and crevice corrosion. Stress corrosion occurred as evidenced
by the transgranular branched cracking found in the bellows and in the base
which was joined to the bellows. It seemed probable that chlorides were
present, which, along with the residual stresses present in the bellows
assembly, created the necessary conditions for stress corrosion to occur.
Crevice corrosion occurred probably due to heavy deposits of solids at the
base of the bellows, which created a condition of oxygen impoverishment.

205.

Kleppe, S. R., "High Pressure Expansion Joint Studies", ASME Paper No.
55-PET-10, July 1955.

The need for a high-pressure expansion joint in a process unit
was encountered by the Esso Research and Engineering Company in the design of
a vapor heat exchanger of a fluid hydroformer. Past failures due to stress-
corrosion cracking of thin-walled, low-pressure expansion joints prompted
rejection of the best commercial high-pressure joint; namely, the torus type.
This was because this shape joint could only be fabricated to a maximum
thickness of 0.078 in. For this installation a thick-walled semitorus

expansion joint was employed, for which an experimental stress analysis was made to establish movement and pressure design limits. These data were then correlated with theory and a general design formula was established.

206.

Klingbeil, E., "Zur Theorie Der Rotationschalen vom Standpunkt Numerischer Rechnungen", Ingr. Arch., 27, pp 242-249, 1959 (in German).

This paper discusses the interrelation of the shell equations of Meissner, Tölke, and Münz. The Münz equations are four first-order coupled equations which are the appropriate form for the direct numerical integration methods. No numerical examples are given.

207.

Klosner, J. M., and Levine, H. S., "Further Comparisons of Elasticity and Shell Theory", Polytechnic Inst. of Brooklyn, PIBAL Rept. No. 689, July 1964.

The problem of an infinite circular cylindrical shell subjected to periodically spaced axisymmetric band loads is investigated using a Reissner-Naghdi higher-order shell theory. The generalized equilibrium equations, which include the effects of transverse normal stress and transverse shear deformation, were successfully uncoupled, and an expression describing the transverse displacement of the median surface was obtained. The solution of this expression was then used to calculate the stress resultants, stresses, and displacements. A comparison of the resulting stresses and displacements with the exact elasticity solution and some lower-order shell-theory solutions of the same problem was carried out for ratios of inner to outer shell radius equal to 0.7, 0.8, 0.87, 0.9, 0.93, and for a ratio of distance between band loads to outer shell diameter equal to 0.2.

208.

Kooistra, L. F., and Lemcoe, M. M., "Low Cycle Fatigue Research on Full-Size Pressure Vessels", Welding J., Welding Res. Suppl., 41, pp 2978-3003, July 1962.

This paper discusses the results of an experimental study to determine the low-cycle fatigue characteristics of full-size pressure vessels incorporating a variety of nozzle configurations of interest to the reactor designer and pressure-vessel industry at large. Numerical data on stress and strain concentration factors, redistribution of strains upon cycling, and a description of cyclic test facilities are included.

209.

Kooistra, L. F., Lange, E. A., and Pickett, A. G., "Full-Size Pressure-Vessel Testing and its Application to Design", ASME Paper No. 63-WA-29d, 1963.

The results of full-size pressure-vessel tests are summarized and used to demonstrate the validity of design procedures developed by others. In

particular, design for low-cycle (plastic) fatigue strength and fracture safety are investigated. The results justify the design stress recommendations made by PVRC to ASME and confirm the NRL fracture-analysis diagram-procedure hypothesis. It is emphasized that full advantage can be taken of high-strength materials only by improvement of fabrication and inspection procedures.

210.

Korneki, A., "A Thin-Walled Toroidal Shell Under Uniform Pressure Load", Rozprawy Inzynierski, $\underline{4}$ (1), pp 119-172, 1956 (in Polish).

This paper presents an approximate solution of the toroidal shell bounded by two parallels and loaded with uniform pressure. Both the homogeneous and particular solutions are obtained by asymptotic theory in terms of tabulated functions. Several examples are presented.

211.

Kornecki, A., "Symmetrical Deformation of a Thin Toroidal Shell of Elliptical Cross Section", Bull. Res. Council of Israel, Sect. C, $\underline{7}$ (1), 1959.

This paper presents an approximate computation method of stress and strain components in a thin-walled toroidal elastic shell of elliptical cross section, limited by two parallels and loaded arbitrarily but symmetrically with respect to the axis of revolution. Making use of E. Meissner's variables and neglecting small terms, the problem is reduced to the determination of a complex function $X(0)$ satisfying a differential equation with suitable boundary conditions. Applying asymptotic methods of integration, the solution in closed form is found, the desired function X being tabulated or expressed by means of simple asymptotic formulas.

212.

Kornecki, A., "Asymptotic Solution of a Toroidal Shell Subjected to Non-symmetric Loads", AIAA Journal, $\underline{2}$ (11), November 1964.

This paper considers an asymptotic solution for a shallow toroidal-shell segment for arbitrary nonaxisymmetric loads varying slowly in the circumferential direction. The solution is obtained as a power series in $\sin \theta$ where θ is the angle between the normal to the shell and the center line. The solution converges only for the condition where the absolute value of θ is less than $x/2$.

213.
    Kraus, H., "A Review and Evaluation of Computer Programs for the Analysis of Stress in Pressure Vessels", Pratt & Whitney Aircraft PWA-2516, October 1963 - September 1964.

    It has long been the aim of the Pressure Vessel Research Committee to put the analysis of pressure vessels on a firmer basis, and as a result, a review and evaluation of existing computer solutions was undertaken. After conducting a literature review of the subject of computer programs for pressure-vessel analysis, the authors of the most promising programs were contacted in order to determine their willingness to furnish copies of their programs and instructions for their use. The field of possibilities was narrowed to four programs whose authors gladly furnished computer decks and instructions for their use. A fifth program was obtained but could not be studied because it was written in a language incompatible with the computer installed at the author's company. This report summarizes the findings. It is arranged into three major parts as follows. The introduction presents a summary of the equations of shell theory, a review of the literature on computer solutions, and a discussion of the main methods of solution that are employed in the computer programs. The section, Comparison of Computer Programs, discusses the most interesting programs which have been found and presents information on the scope of each, ease of use, running time, numerical results for sample cases and so on. Finally the Discussion and Conclusion sections give a summary of experiences with an evaluation and recommendations.

214.
    Kudrin, N. S., "The Strained State of a Folded Sinusoidal Shell", Izv. AN SSSR, OTN, Mekh. i Mash., 5, pp 149-150, 1959 (in Russian).

    This note considers a bellows with shallow sinusoidal convolutions. The author considers axial and pressure loads as well as thermal stresses. Formulas are developed on the assumption that the corrugation depth is small compared to the cylinder diameter. Some calculations are made showing the thermal stresses for different corrugation depths.

215.
    Kumasaka, T. T., and Barnet, J. W., "Predicting Metalworking Properties From Tensile Test Data", Metal Prog., pp 84-86, March 1965.

    The fabricating characteristics of metals and nonmetallics can be rated by numerical factors derived from tensile-test data. Once the basic equations are derived, the method is simple. Experience in the shop confirms the ratings.

216.
    Lakhtin, A. A., "Calculation of Certain Elements Which Include Torus-Shaped Parts", Inzh. sb., 25, pp 66-77, 1958 (in Russian).

    The asymptotic theory of Novozhilov is used to develop tables of influence coefficients for semitoroidal shell segments.

217.
Lamont, E. A., "The Development of Advanced Cryogenic Pressure Switches For Ballistic Missiles", Freebank Co., March 1960 (AD 240155).

This report describes a research and development program for the development of advanced cryogenic pressure switches. Two novel-pressure switch concepts using diaphragms were discovered and proven experimentally. Advanced techniques of omnienvironmental testing were employed. One switch was developed that was adjustable between 100 and 1000 psia. Another switch developed was adjustable for actuation between 10 and 100 psig. Both switches had a unique deadband adjustability.

218.
Langer, B. F., "Design of Pressure Vessels for Low-Cycle Fatigue", J. of Basic Eng., pp 389-402, September 1962.

Methods are described for constructing a fatigue curve based on strain-fatigue data for use in pressure-vessel design. When this curve is used, the same fatigue strength-reduction factor should be used for low-cycle as for high-cycle conditions. When evaluating the effects of combined mean and alternating stress, the fatigue strength-reduction factor should be applied in both the mean and the alternating component, but then account must be taken of the reduction in mean stress which can be produced by yielding. The complete fatigue evaluation of a pressure vessel can be a major task for the designer, but it can be omitted, or at least drastically reduced, if certain requirements can be met regarding design details, inspection, and magnitude of transients. Although the emphasis in this paper is on pressure-vessel design, the same principles could be applied to any structure made of ductile metal and subjected to limited numbers of load cycles.

219.
Laupa, A., and Weil, N. A., "Analysis of U-Shaped Expansion Joints", J. Appl. Mech., pp 115-123, March 1962.

An elastic analysis of U-shaped expansion joints under axial loads and internal or external pressure is presented. The analysis employs the energy method for the toroidal sections, and the theory of symmetrical bending of circular plates augmented by thick-walled cylinder analysis for the annular plate connecting the two toroidal sections. The general solution permits the investigation of any U-shaped expansion joint falling in the range of thin shells, for any arbitrary combination of axial force and pressure loading. Different forming radii may be assigned to the inner and outer toroidal sections, and it is permissible to vary the average thicknesses of the two toroidal sections and the interconnecting annular plate independently. Expressions are given for the load-extension and load-stress characteristics of U-shaped expansion joints, and a numerical example is presented comparing the present solution with results of existing approximate analyses. The method presented here lends itself readily to programming on an electronic computer.

59

220.
Lazan, B. J., "Creep-Fatigue Interacting Under Cyclic Loading Conditions", AFSC, Aeron. Systems Div., ASD-TDR-63-644, May 1963.

The limitations imposed by synergistic or interaction phenomena on the validity of linear superposition and summation approaches are discussed. In particular, single-variable data are shown to be generally inadequate for predicting mechanical properties under combined loads and environments. The immensity of a testing program required to investigate all important combinations of load and environment is illustrated and the significant reductions possible if synergisms are known is demonstrated. The operative micromechanisms and synergisms under combined static and fatigue loading are discussed, with particular reference to microstructural changes of mechanical and chemical origin. Analytical methods for predicting creep and rupture under variable stress from static creep data are reviewed and compared with experimental results.

221.
Lee, G. H., and Van der Pyl, L. M., "Bibliography on Diaphragms and Aneroids", ASME Paper No. 55-A-180, 74 pp, 1955.

This is a comprehensive annotated bibliography of the available published data on diaphragms and aneroids up to the end of 1954.

222.
Lepik, Yu. R., "Equilibrium of Elastic-Plastic and Rigid Plastic Plates and Shells", Inzh. Zhur., $\underline{IV}$ (3), pp 601-616, 1964 (in Russian).

This is a survey article of the developments of the elasto-plastic theory of plates and shells for about 20 years prior to 1962. The bibliography includes 160 Russian papers and 91 non-Russian papers.

223.
Li, Y. T., "High-Frequency Pressure Indicators for Aerodynamic Problems", NACA Tech. Note 3042, 52 pp, 1953.

Three different types of pressure indicators developed at the Massachusetts Institute of Technology are discussed in this paper. Each of these indicators has a unique feature, but all were designed in an attempt to combine both high-frequency response and high resolving power into one instrument. Of the mechanical-electrical-transducer type of pressure indicator, the wire strain gage leads in simplicity. The capacitance type is more versatile because it permits the use of very high frequency carrier systems and thereby cuts down the effective interference in the electronic system. The system utilizing the stretching of a barium-titanate disk produces large signals and results in compact design, but it can only be used for dynamic measurements when temperature variations are slight. Five different types of pressure receivers, the cylinder, flat-diaphragm, spherical-diaphragm, catenary-diaphragm, and stretched-diaphragm or membrane types, were tested. The flat-diaphragm type leads the others in simplicity, the spherical-diaphragm type exceeds in dynamic performance, and the catenary-diaphragm type is the one least affected by temperature change.

224.

Listrova, Yu. P., and Rudis, M. A., "Limit Equilibrium of a Toroidal Shell", Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, Mekh. i Mash., 3, pp 199-123, 1963 (in Russian).

This paper considers the limit load of a semitoroidal shell clamped at $\phi = 0$ and $\phi = \pi$. For this case the shell is nearly in a membrane stress state. It is assumed that the shell is made of rigid-plastic material and is loaded by pressure.

225.

Little, R. E., "A Simplified Method for Determining Fatigue Stress Using Mohr's Circle", Machine Design, pp 143-148, March 4, 1965.

Fatigue cracks are initiated by alternating shear stress and propagated by alternating normal stress. Consequently, maximum amplitude of these stress components must be calculated in fatigue analysis. Mean stress components acting on the planes of maximum amplitude of alternating stress also influence fatigue strength and must be determined. This article shows how Mohr's circle can be used to determine and visualize easily and quickly these components of cyclic stress. This approach also provides a convenient means of interpreting visually fatigue-test data for various states of combined stress with superimposed mean stress.

226.

Losco, W. F., et al., "Pressure-Deflection and Fatigue Properties of Zircaloy Diaphragms", Bettis Atomic Power Lab., WAPD-T-1228, 63 pp, July, 1960.

Plate type fuel elements containing compartmented and unbonded ceramic fuel are of considerable interest because of their high thermal performance and long life capabilities. The unbonded Zircaloy cladding over individual fuel compartments in these plates are essentially thin diaphragms, fixed at the edges, and are subject to deformation under the action of hydrostatic pressure. The pressure-deflection and fatigue characteristics of such diaphragms, under a variety of out-of-pile temperature and pressure conditions, have been determined and are described in this paper.

227.

Low, E. D., "The Use of Pneumatic Diaphragm Units", Instr. Eng., 2 (5), pp 85-91, April 1958.

The principles of operation of pneumatic diaphragm units are described. Their use in performing simple operations with air-pressure signals is indicated, and it is shown how they may be over-connected to provide more complex air-pressure relationships. Examples are given of their application to automatic control.

228.
Lyon, F. H., and Grover, H. J., "Some Suggestions for Research in Diaphragm Technology", ASME Paper No. 56-A-221, 9 pp, November 1956.

A number of suggestions for research had appeared in the literature and others had been advanced to the ASME Diaphragm Subcommittee. These are discussed in this paper from the design viewpoint. The presentation is intended to provoke discussion and suggest possibly illuminating approaches to certain problems.

229.
McClaren, S. W., and Best, J. H., "Plastic Strain Accumulation - New Fatigue Life Forecaster?", SAE Journal, 73 (9), pp 68-75, September 1965.

The behavior of a group of aerospace materials under repeated loads at high uniaxial and biaxial stress levels to produce low-cycle-fatigue damage has been evaluated. The results suggest that plastic-strain accumulation may be a better predictor of fatigue life than Miner's theory.

230.
McKinney, G. E., "Metal Bellows", Mech. Eng., 79, pp 573-574, June 1957.

As discussed in this article, the formation is one of the more difficult steps in bellows manufacture, since final wall thickness is rarely more than 0.004 in. to 0.010 in. Extremely careful control of tube dimensions is mandatory, since the characteristics of the finished bellows depend in a very large degree on the condition of the metal, the final dimensions, and uniformity of the walls in the bellows tube.

231.
"Machined Bellows are Light, Resist Fatigue", Space/Aeron., 30, pp 60-63, December 1958.

The article describes the advantages of machined bellows. Methods of fabrication and application are outlined and typical size ranges are given.

232.
Makarov, V. M., Lakhtin, A. A., and Lovtskiy, E. V., "The Possibility of Using Convoluted Bellows Under High Pressures", Khim. Mashinostr., 3, pp 26-29, 1959 (in Russian).

This paper gives some experimental measurements of stress for a semi-toroidal and U-shaped bellows under internal pressure and axial loads and compares them with a theory developed by Lakhtin (not described).

233.

Marcal, P. V., and Turner, C. E., "Elastic Solution in the Limit Analysis
of Shells of Revolution With Special Reference to Expansion Bellows", J. Mech.
Eng. Sci., 3 (3), pp 252-257, September 1961.

The elastic solution is used to calculate lower and upper bounds for symmetri-
cally loaded shells of revolution. In order to obtain the upper bound, a
number of circumscribed yield surfaces are used to introduce a flow mechan-
ism. The results obtained are compared with experimental and other limit-
analysis results.

234.

Marcal, P. V., and Turner, C. E., "Numerical Analysis of the Elastic-Plastic
Behaviour of Axisymmetrically Loaded Shells of Revolution", J. Mech. Eng.
Sci., 5 (3), pp 232-237, 1963.

Equations have been derived which enable a numerical analysis of axisymmetri-
cally loaded shells of revolution to be made. These equations apply equally
to small or large deflection shell theory with linear or nonlinear stress-
strain laws. Numerical results are presented for the case of an elastic-
plastic axially loaded corrugated expansion bellows.

235.

Marin, J., Paper from Progress in Applied Materials Research, VI, pp 3-39,
1964, Gordon & Breach, New York.

This paper surveys the fields of plastic and creep properties of engineering
materials as related primarily to the macroscopic stress-strain or mechanical
behavior of materials.

236.

Martin, D. E., "An Energy Criterion for Low-Cycle Fatigue", ASME Trans.
83D, 4, pp 565-571, December 1961.

A low-cycle fatigue criterion is proposed which employs as an index of damage
the portion of the plastic-strain hysteresis which is associated with the
work-hardening segment of the stress-strain relation. This damage work-energy
relation provides a theoretical basis for the plastic strain-cycle equation:
$N^{1/2} \Delta\epsilon = C$, which was previously advanced empirically. The constant C in
this equation had previously been approximated by Coffin (AMR 14(1961), Rev.
3562) on the basis that a tensile test is equivalent to a 1/4-cycle fatigue
test. Author evaluates C on the basis of energy absorbed during work-
hardening alone in static tensile tests. If ϵ_f is the static fracture
ductility he finds C equal to ϵ_f divided by the square root of 2 while Coffin
has found C equal to ϵ_f divided by 2. Author compares his value with pub-
lished low-cycle fatigue tests to find better agreement for room-temperature
tests than Coffin but poorer agreement for elevated-temperature data.

237.

The Martin Company, Test Rept. No. 11006, "Evaluation Test of Insulated Flexline", July 31, 1961 (AD 283714).

This report presents the test procedures used and the test results obtained during the evaluation of an insulated 2-in. flexible tubing connector designed for use with nitrogen tetroxide propellants. The tests included nitrogen flow (18-21 lb per min., 15 psi, 400 F), nitrogen and nitrogen-tetroxide flow (14-1 lb per min., 13 psi, 100 F), and static pressure (75 psi).

238.

The Martin-Denver Co., "Qualification Test Report of Aluminum Welded Bellows", August 23, 1961. IDEP 115.70.69-00-F3-01.

The tests of a 13-inch-diameter aluminum bellows included visual examination, proof pressure (35 psig), spring rate determination, ultimate pressure (90 psig), and life cycling (450 compression cycles).

239.

The Martin-Denver Co., "Flight Certification Test on Oxidizer Pressure Line", December 26, 1961 (AD 295351).

Tests of two flexible metal hose assemblies included visual examination, pressure and deflection cycling, leakage (bubble), pressure (165 psig), pressure drop (1.43 lb/sec GH$_2$), vibration, operational cycling, and burst (1650 psig).

240.

The Martin-Denver Co., "Flight Certification Test on Pressurization Line", December 1, 1962 (AD 296626).

Tests of two flexible metal hose assemblies included visual examination, life tests (45 psig pressure, deflection and misalignment cycling), proof pressure (205 psig), vibration, flow, operational cycling, and burst (820 - 1010 psig).

241.

The Martin Company, "Qualification Test Report of Flexible Metal Bellows", T.R. 2111, June 22, 1961. IDEP 115.70.69.00-F3-02.

Tests of a 4-inch welded bellows included spring rate, pressurization (external to 70 psi), life cycling under pressure with full extension and compression (450 cycles), and ultimate pressure (120 psi).

242.

The Martin Company, "Metallurgical Investigation of Leakage in Missile, B-66 Stage II Oxidizer Feed Line Bellows", June 15, 1964. IDEP 115.76.69.00-F3-01.

A nitrogen tetroxide leak was caused by stress corrosion between the inner and outer plys because of entrapment of chloride-containing contaminants. Because residual stresses caused by forming methods and installation requirements can always be expected, cleanliness between the two plies is of the utmost importance.

243.

Matheny, J. D., "Bellows Spring Rate for Seven Typical Convolution Shapes; Data Sheet", Machine Design, 34 (1), pp 137-139, January 4, 1962.

A bellows is analogous to a spring. Several theories have been developed to give load-deflection relationships for different bellows configurations. Formulas based on these theories are presented for determining the spring rates of 7 typical convolution shapes.

244.

Matheson, H., and Eden, M., "A Highly Sensitive Differential Manometer", Rev. Sci. Inst., 19, pp 502-596, 1948.

This paper describes the construction and performance of a differential manometer with a sensitivity of 0.001 mm of mercury over the range of absolute pressures from 1 mm of mercury to 1 atmosphere. The sensitive element employed is a pair of nesting diaphragms, displacement of which is measured by the resistive unbalance of an unbonded electrical displacement gage to which the diaphragms are attached. Calibrations are presented for the sensitivity at 1- and 10-ma gage current. Data are presented which indicate the operating characteristics under varying conditions of absolute pressure, temperature, gage current and geometric orientation.

245.

Mathews, C. C., "Picking Metal Tubing for Flexing Uses", Mater. in Design Eng., May 1964.

Constant metal movement makes tubing used in flexing parts prone to fatigue failure. This discussion of flexing applications is not limited to those end uses specifically designed to provide flexing action, i.e., Bourdon tubes, bellows, flexible metal hose, etc. It includes those applications where metal movement is unwelcome and usually caused by pressure surges or equipment vibration, i.e., pressure tubing, hydraulic lines, diesel engine fuel lines, aircraft parts, etc.

246.
Matt, R. J., "High Temperature Metal Bellows Seals for Aircraft and Missile Accessories", J. of Eng. for Ind., pp 281-283, August 1963.

In this article the following conclusions are made: (1) seals operating over a wide temperature range require greater precision and design analysis than the standard cartridge seals used in most rotary equipment, (2) the effect of flatness on sealability is of prime importance and this flatness must be maintained over the entire environmental range of the seal assembly, (3) seal-ring flatness in the operating position is more important than flatness in the unloaded state because sealing is required in a loaded position, not in the free position, (4) as speed increases, the problems of cam hop and fatigue also increase, (5) the runout and surface quality of the mating ring is of paramount importance, and (6) the selection of bellows materials and heat-treatment have a definite effect on operating life and continuous quality control must be maintained on the assemblies to guarantee the high reliability that is required for aircraft and missile components.

247.
Meher, R. L., "Component Gimbal Joint Bellows Liquid Oxygen Engine Feed Lines", Solar Rept. RDR 1434, June 26, 1964, IDEP 115.16.75.00-F1-02.

The development tests of the gimbal joint bellows (7.9 inches diameter, 2 ply, Inconel 718), included determination of axial spring rate (compression) the angular spring rate (deflection through 6 degrees), angular fatigue life (with internal pressure of 103 psig), and pressure stability (12 deg. angulated position, pressurized to failure).

248.
Mellor, P. B., "The Ultimate Strength of Thin-Walled Shells and Circular Diaphragms Subjected to Hydrostatic Pressure", Intern. J. Mech. Sci., $\underline{1}$ (2/3), pp 216-223, April 1960.

The ultimate strength of thin-walled cylinders, spherical shells and circular diaphragms subjected to hydrostatic pressure is investigated for materials where strain-hardening characteristics can be fitted by the empirical equation $\bar{\sigma} = A(B + \bar{\epsilon})^n$. Experimental values of maximum pressure obtained in the deforming of circular diaphragms of initially cold-worked materials are shown to be in good agreement with a theoretical treatment by Hill.

249.
"Metal Bellows", Metal Ind., $\underline{70}$ (4), pp 69-70, January 24, 1947.

A brief description is given of the hydraulic method of forming metal bellows. This involves unrestricted flowing of a thin-walled metal tube under considerable hydraulic pressure in a collapsible die, the latter comprising a number of plates equal to the number of convolutions and spaced equidistant, on and surrounding the tube. The metal flows transversely between the plates under this internal pressure, the tube being collapsed endwise as pressure is applied, the bellows thus being formed in one continuous operation.

250.

"Metal Bellows", Process Control, 2 (5), pp 173-177, May 1955.

Bellows are used in a great number of instruments and in other equipment but many users are handicapped by a lack of sufficient information on the subject. This article is designed to help by discussing some of the more important points. The particular types described are hydraulically formed metal bellows, but apart from the method of manufacture and the special qualities these possess, the article applies equally well to other types.

251.

"Metal Bellows", Mech. Eng., 79, pp 573-574, June 1957.

A brief description is given of the design and manufacture of formed bellows.

252.

"Method for Selecting a Metallic Bellows", Design News, 8 (16), pp 57, 59, 61, August 15, 1953.

After selecting the proper bellows system, the designer is faced with the problem of determining the exact bellows specification. The problems entering into this calculation are those of determining the operating characteristics of the system. The factors entering into these calculations are first, the natural spring-resistance of the bellows; second, the resistance of the opposing adjusting spring strength; and third, the functional resistance of the valve or switch mechanism excluding the adjusting spring. Information is given in the article to assist the designer.

253.

Meyer, R. R., and Harmon, M. B., "Conical Segment Method for Analyzing Open Crown Shells of Revolution for Edge Loading", AIAA J., 1 (4), pp 886-891, April 1963.

A solution, accurate, rapid, simple enough for design use, and valid for all regions, has been obtained for the stress distribution and influence coefficients for a variable thickness shell of revolution formed by a generator of arbitrary shape. The shell is subdivided into a series of equivalent conical segments whose individual thicknesses are the local segment average. Conditions of continuity then are applied at the boundaries of each conical segment to evaluate the indeterminate edge shears and moments using digital equipment. Influence coefficient comparisons for a wide range of shell geometries are made between the cone solution and solutions by other methods from the literature and show agreement within 4 percent. The cone solution reciprocity relations are shown to be valid to five significant figures. Limiting conditions indicate that good approximations of the influence coefficients and the stresses can be obtained by using 10 cones in most cases.

254.

Miles, D. O., "Direct Mechanical Determination of the Dynamic Response of Diaphragms", J. of the Acoust. Soc. of Am., 36 (8), pp 1471-1478, August 1964.

The freefield resonant frequency and the deflection under given static pressure of a thin, circular, clamped-edge diaphragm may be calculated theoretically by well-known equations. Also, experimental means exist for a determination of these quantities. No satisfactory theoretical or experimental method has appeared, however, by which it is possible to obtain, for a complicated physical system, the diaphragm deflection as a function of the frequency of an applied sinusoidal pressure, over a frequency range that includes the natural diaphragm resonance. An experimental method is described by which a piezoelectric driver is employed to generate a sinusoidal pressure of variable frequency in a confined gas, to which one side of a test diaphragm may be exposed. Equations are derived describing the gas-coupling medium and the piezoelectric driver. By use of these equations, it is possible to predict the characteristics of the apparatus. Modifications of the apparatus are reported that extend the dynamic-pressure amplitude and the useful frequency range, and the possibility of utilizing the apparatus for dynamic calibration of pressure gages is noted.

255.

Miller, D. R., "Bibliography on Thermal Stresses and Low Cycle Fatigue", Knolls Atomic Power Lab., Report KAPL-2048, August 20, 1959.

This bibliography consists principally of references to domestic publications on subjects that pertain to thermal stresses and low-cycle fatigue in nuclear reactors and power apparatus. Both major subjects are included in the same bibliography, because cyclic thermal stresses or thermal-differential strains are frequently sufficiently high to cause fatigue cracking on the order of 100,000 cycles or less. The problem of fatigue cracking in this range of cycles-to-failure is considered low-cycle fatigue. The references are placed, according to the character of the principal content, in the following groupings: Material Test Data, Service Experience and Component Tests, Stress Analysis, Design, and Miscellaneous.

256.

Miller, D. R., "Thermal-Stress Ratchet Mechanism in Pressure Vessels", ASME Paper No. 58-A-129, 1958.

The combination of cyclic thermal stresses and sustained internal pressure in a vessel is shown to be a source of progressive expansion of the vessel if the stresses are sufficiently high. Criteria presented allow determination of limits to be imposed on stresses in order to prevent progressive expansion or to allow estimation of the expansion per cycle where stresses are sufficient to produce growth. The effect of strain-hardening of the metal on progressive reduction of the growth rate is discussed.

<u>257.</u>

Mirabal, J. A., and Dight, D. G., "SOR-II, A Program to Perform Stress Analysis of Shells of Revolution", General Electric Company Rept. KAPL-M-EC-19, UC-32, June 1, 1962.

This report describes a computer program developed at Knolls Atomic Power Laboratory. The program solves for the forces, deflections, stresses and strains in thin shells of revolution. The shells may be general surfaces of revolution with variable thicknesses and elastic moduli. The axisymmetric loadings considered include arbitrary distributions of normal, tangential and moment surface loadings, as well as edge forces and deflections. The effects of temperature variations in the meridional and thickness directions as well as centrifugal loading due to rotation about the axis and vibration are included. The additional effects of misalignment, line loads, and elastic supports at the shell intersections are considered. The program numerically integrates the shell equations using a generalized Adams-Moulton method. The integration proceeds along the shell with automatic adjustment of interval size for maximum speed within the limitations of the preset error bounds. The integration error bounds, which may be altered by input, are preset to give for most cases, four significant figure accuracy. The method used permits solution of problems in which the shell includes the axis of revolution. It also allows step changes in loadings and some shell properties. Although most of the program is written in FORTRAN, a number of subroutines are written in Philco 2000 assembly language, which limits use of the program to this machine.

<u>258.</u>

Morrow, JoDean, and Johnson, T. A., "Correlation Between Cyclic Strain Range and Low-Cycle Fatigue Life of Metals:, Mater. Res. and Std., 5, pp 30-32, January 1965 (A65-14624).

An evaluation is described of available data on the fatigue lives of 48 metals (including 21 steels, 2 cast nickel-based alloys, and a hot-pressed beryllium) to assess which of the three suggestions (due to Coffin, to Manson, and to Peterson) for a universal value of cyclic strain that would provide approximately the same fatigue life for all metals, gives the best correlation with the data. A tabular comparison of the three rules of thumb proposed clearly shows that Peterson's suggestion that ±1 percent strain causes failure in about 1000 cycles gives the best agreement with the central tendency of the experimental results, and has the least scatter. None of the three suggested rules, however, gives particularly safe estimates.

<u>259.</u>

Minz, H., "Ein Integrationsverfahren fur die Berechnung der Biegespannungen Achsensymmetrischer Schalen unter Achsensymmetrischer Belastung", Ing-Arch., 19, pp 103-117, 1951 (in German).

Minz treats the analysis of axisymmetrically loaded shells of revolution by use of the calculus of variations. With this approach it is possible with the use of known integrals, to reduce the sixth-order system to a system of four first-order differential equations for which numerical-integration methods are applicable. No numerical examples are included.

260.
     Murphy, G., "Analysis of Stresses and Displacements in Heat-Exchanger Expansion
     Joints", ASME Trans., 74, pp 397-402, April 1952.

     This paper presents a procedure for the analysis of stresses and displacements
     in an expansion joint, when the latter is assumed to be a surface of revolu-
     tion. The analysis as presented employs a method of successive approximations,
     but in general, the solution will be rapidly convergent. Possible thermal
     gradients in the joint are not included in the analysis as given, but may be
     introduced in the solution.

261.
     Nakamura, K., "The Tables of the Functions for the Stress Analysis of the
     Toroidal Shell of Circular Cross Section", Bull. Fac. Eng., Yokohama Nat. Univ.,
     10, pp 25-49, March 1961.

     In spite of many investigations, the analysis of stresses in the toroidal shell
     of circular cross section is somewhat difficult for practical use. This may
     be partly due to the fact that such analysis requires a considerable amount
     of numerical work. The author has developed a general method of solving the
     toroidal-shell problem, which permits this difficulty to be overcome.

262.
     Nakamura, K., "A Contribution to the Analysis of Stresses in the Toroidal
     Shell of Circular Cross Section", Bull. Fac. Eng., Yokohama Nat. Univ., 6,
     pp 103-109, March 1957.

     Most practicable pressure-vessel heads have profiles made up of two circular
     arcs. To analyze the stresses in such vessel heads rigorously, calculations are
     based on the Love-Meissner theory, but the shell-theoretic calculations usually
     involve a great deal of numerical work. In this investigation, tables of solu-
     tions of the simplified basic equations for the toroidal shell were calculated.
     These tables which are valid within the limited range of interest are presented.

263.
     Neal, Molly, "Survey of Expansion Joints for Pipework Systems, I", Eng. Mater.
     and Design, 8, pp 168-175, March 1965.

     This article contrasts the respective advantages of rubber expansion joints,
     slip joints, and various forms of bellows joints, and surveys the units cur-
     rently available.

264.
     Newell, F. B., "Diaphragm Characteristics, Design, and Terminology", ASME,
     New York, 74 pp. 1958.

     An effort has been made to describe diaphragm characteristics in a logical
     arrangement, and to show how they are affected by changes in material, dimen-
     sions, and treatment. The manual is divided into two principal parts: The

first defines a diaphragm and its performance characteristics, describes some methods of measuring and representing them, and shows how they are related and used; the second part deals with ways in which diaphragms can be constructed and how various design details and treatments affect performance characteristics.

265.

Newland, D. E., "Buckling of Double Bellows Expansion Joints Under Internal Pressure", J. Mech. Eng. Sci., $\underline{6}$ (3), 1964.

Corrugated bellows expansion joints may buckle under internal pressure in the same way as an elastic strut may buckle under an axial load. This paper is concerned with the analysis of this phenomenon for the "universal expansion joint" which incorporates two bellows joined by a length of rigid pipe. The principal conclusion is that, by providing a correctly designed supporting structure, the critical buckling pressure can be increased to up to four times in value for the same system with no supports.

266.

Nippes, E. F., and Fishman, H. B., "Optimum Spot and Seal Welding Conditions for Inconel X", Welding J., Welding Res. Suppl., $\underline{33}$, pp 1s-4s, January 1954.

This paper describes the determination of the optimum spot and seam welding conditions for 0.010, 0.015, 0.021, 0.031, and 0.062-inch Inconel X sheet. Inconel X is a precipitation-hardening alloy for high-temperature use. The unique properties of Inconel X and their effect upon spot and seam welding are discussed.

267.

Nolte, C. B., "History of Bellows-Actuated Flow Meters", Instruments, $\underline{23}$ (1), pp 79-84, January 1950.

This article describes in some detail different types of flow meters and the development of bellows-actuated flow meters. Advantages of the various configurations are explained.

268.

Nolte, C. B., "Rupture-Proof Bellows-Type Flow Meters", ISA Proc., $\underline{5}$, pp 44-47, 1950.

A brief history is given of the development of bellows-type flow meters which would not be ruptured by overpressure.

269.

North American Aviation, Space and Information Systems Divn. Test Rept., "LH$_2$ Feed Line Components, Saturn S-II", March 6, 1964.

Prior to the tests and results described, problems were encountered with the

original bellows design. A combination of small convolution radii and tee-thick weldments created premature fatigue failures. A design change was made and weld-thickness control was improved. Bellows and gimbal assemblies were then subjected to bending cycle fatigue tests (4400 cycles) both at room temperature and at LN_2 temperature while pressurized at 88 psig. The cycle life exceeded the endurance requirements. In order to verify and supplement theoretical calculations of the gimbal joint analysis, strain gages were applied in critical areas on the gimbal joint during the pressure tests. In addition, a stress coating was applied to verify the accuracy of strain-gage locations.

270.

Norwood, D. L., "Sheet Metal Formability at Ambient Temperature", Metals Eng. Quart., 5 (1), pp 41-51, February 1965.

A method was developed for predicting formability from the geometrical parameters and the mechanical properties of the material. This article describes how it can be applied to predict the sheet-metal formability for any material used in the 12 most important conventional forming processes.

271.

Nothdurft, H., "The Characteristics of Metal Bellows", Regelungstechnik, 5 (10), pp 334-338, 1957 (in German).

In the use of metal bellows the following characteristics are of interest: (1) elasticity, (2) permissible stroke length, (3) pressure resistance, (4) critical capacity, (5) effective area, and (6) durability. Attempts to find some of these parameters with the aid of equations used in the theory of plates gave results that disagreed with values found by experiment. Methods for the measuring of these parameters are therefore described and the results of these experiments are stated in the form of approximation equations.

272.

Novickis, G., "Survey of Component Requirements and Availability for Gas-Cooled Nuclear Reactor Power Plants", The Franklin Institute, October 1962.

This report, a result of a literature survey and responses from manufacturers, was written to assess the state of the art in design requirements and availability of reactor pressure vessels and supports, valves, expansion joints, and piping for primary circuits in gas-cooled reactors. 79 reactors are listed. The above-mentioned equipment for these reactors is described and discussed, and lists of manufacturers are included.

273.

Novoshilov, V. V., *Thin Shell Theory*, Translation of 2nd Edition, P. Noordhoff, Ltd., Groningen, The Netherlands, 1964.

This is one of the classical Russian books on shell theory. The first part of the book presents the derivation of the equations for arbitrarily shaped shells. The remainder of the book is devoted to discussion of shells of particular shapes. A considerable portion of the book is devoted to the complex formulation of the equations for shells of revolution. The asymptotic solution of a number of shells of constant curvature is discussed in considerable detail.

274.

Nunn, H. D., "A Guide to Static-Pressure Transducers That Have Diaphragm, Bellows, or Bourdon Pressure Cells", Prod. Eng., 30 (1), pp 48-49, January 1959.

This article describes pressure transducers which sense pressure directly and continuously, as simple Bourdon pressure gages do, and which convert the resulting movement or position of the pressure element into electrical units. "Static" here means low-frequency response--less than 4 cps. Another article, on piezoelectric transducers, covers higher frequencies.

275.

Onat, E. T., and Haythornthwaite, R. M., "The Load-Carrying Capacity of Circular Plates at Large Deflection", J. Appl. Mech., 23 (1), pp 49-55, 1956.

This paper presents an approximate analysis for the load-carrying capacities of initially flat circular plates under various loading and edge conditions and subjected to slowly increasing load. The load capacity after finite deflection is estimated by assuming a velocity field based on the boundary conditions and on the incipient velocity field of the flat plate, the analysis being made for a rigid plastic, nonstrain-hardening material that yields according to the maximum shear-stress criterion. In several cases the results obtained compared favorably with test data for mild-steel plates; however, for very thin plates, better agreement was obtained by means of a purely membrane-type analysis, which is also presented.

276.

Op het Veld, A.J.G., "Cr-Ni Steel Grades at Low Temperatures (Below -180 C)", Metalen, 20 (4), pp 105-115, April 1965 (in Dutch).

A critical survey of the mechanical properties of austenitic Cr-Ni steels at and below -180 C is presented. Attention is given to the influence of different structural factors, such as cold deformation, and the presence of martensite, ferrite, sigma phase, carbides, and nitrides on mechanical behavior.

73

277.

Osilova, L. N., and Tumarkin, S. A., Tables for Analysis of Toroidal Shells, Moscow, Akad. Nauk SSSR, 91 pp, 1963 (in Russian).

Extensive tables, based on the asymptotic solution of toroidal shells by Novozhilov are presented to permit the hand calculation of toroidal shells. Functions are tabulated in intervals of one degree in meridional angle and 0.01 in the parameter:

$$\alpha = \frac{R_o}{r_o}, \quad o \leq \alpha \leq 1,$$ where r_o is the radius of the center of the torus from the axis of symmetry and R_o is the radius of the torus.

278.

Osterman, J. A., "Study and Preliminary Design of a Hermetically Sealed Hydraulic System", Lockheed Georgia Company, August 24, 1962 (AD 285847L).

Investigations of techniques for hermetically sealing hydraulic components and systems were conducted, and the preliminary evaluation and selection of internal seals, hermetic sealing devices, and new system concepts were completed. Tentative requirements and design criteria for hermetically sealed components and systems are described in the first quarterly progress report.

279.

Ota, T., and Hamada, M., "On the Strength of Toroidal Shells", Part 1, A Proposition on the Solutions, Part 2, Examples of Solutions, Bull. Japan Soc. Mech. Eng., 6 (24), pp 638-654, 655-665, November 1963.

A method for solving the fundamental differential equations for the symmetrical problems of toroidal shells is proposed in this paper. The perturbation method is used, and the solutions are obtained in such a form that the numerical values of the solutions may be easily found, if the values of the parameters are given. The ranges of the values of the parameters in which the solutions are available with satisfactory accuracy are checked.

280.

Palmer, P. J., "An Approximate Analysis Giving Design Data for Corrugated Pipes", Proc. Inst. Mech. Eng., 174 (20), pp 635-641, 1960.

This paper gives an approximate method of analysis for corrugated pipes and ducts, of the type in which the corrugations have a constant radius of curvature. The method is applicable to corrugations of any included angle, provided that the radius of curvature of the corrugation is small compared with the radius of the pipe. The analysis is carried out using the principle of minimum strain energy, in which the smallest possible number of terms are employed. The advantage of the method is that results giving extension, bending stress, and circumferential stress can be evaluated for corrugations with different included angles, and simply presented in graphical form. These results are then readily available for design considerations covering corrugated pipes with

internal pressure, axial load, and bending moment. The approximate results are compared, where possible, with some results from more precise methods of analysis, and also with some experimental results, and the comparison shows the present method to be sufficiently accurate for design considerations.

281.

Palmer, P. J., "A Method of Analysis for Axially Symmetrical Shells With Constant Meridional Curvature", Quart. Mech. Appl. Math., 12 (4), pp 431-442, 1959.

This paper gives a theoretical method of analysis for shells of constant thickness forming a surface of revolution with axially symmetrical loading and with constant meridional curvature. The method of solution is to solve directly the basic differential equation governing the problem. The method is comprehensive and applies to a wide range of design problems, although in the present instance it is used to determine the stresses in pressurized corrugated ducting.

282.

Patterson, J. L., "A Miniature Electrical Pressure Gage Utilizing a Stretched Flat Diaphragm", NACA Tech. Note 2659, 47 pp, 1952.

A variable-air-gap inductance type of electrical pressure gage is described that is basically 7/16 inch in diameter and 1/4 inch in thickness. The gage was designed to measure pressures fluctuating at high frequencies. It is also capable of measuring steady-state pressures with errors of less than 1 percent of full scale and has proved to be of value as a general-purpose electrical gage for aeronautical work where small size and minimum response to acceleration forces are important factors. Design equations and curves are presented which can be used to predict the deflections and fundamental natural frequencies of stretched flat diaphragms.

283.

Payne, D. J., "Numerical Analysis of the Axisymmetric Bending of a Toroidal Shell", J. Mech. Eng. Sci., 4 (4), pp 356-364, 1962.

Finite difference approximations are used to analyze a symmetrically loaded toroidal shell. It is shown that the equations derived by E. Reissner in terms of $H_\varphi r_0$ (the product of the radial force per unit circumference normal to the axis of revolution and the radius measured normal to the axis) and V (rotation of the meridional tangent) avoid the difficulties which occur, owing to a singularity at the pole circle of a toroidal shell, when Meissner's equations in terms of $U = Q_\varphi r_2$ (the product of the lateral shear force per unit circumference and the second principal radius of curvature) and V are used. A numerical example is solved with both forms of the equations. The values obtained for H_φ, Q_φ, and V differ by less than 1% near the edge of the shell but in the region of the pole circle there is no correlation between the two sets of results. Comparison with Turner's analytic solution shows that the values and positions of the maxima and minima differ by up to 6% and 5 deg. respectively.

284.

Penny, R. K., "Axisymmetric Bending of the General Shell of Revolution During Creep", J. Mech. Eng. Sci., 6 (1), pp 44-46, 1964.

There are many applications in various fields of engineering where 'thin-shell' theory can be used to give adequate solutions to practical problems. Although a lot of attention has been devoted toward solving the elastic shells, relatively few investigations of shell behavior in which plasticity or creep occur have appeared. In dealing with the creep of cylindrical shells, Poritsky followed the procedure outlined by Mendelsohn and others for solving plate and disc problems. A different approach used by Onat and Yüksel or by Calladine dealing with edge-loaded cylinders would require further development before it could be used in practical problems. The present purpose is to extend the method of Mendelsohn to the general shell of revolution which is loaded and heated axisymmetrically.

285.

Peterson, R. E., "The Role of Stress Distribution in Fatigue", Exptl. Mech., 1 (4), pp 105-115, April 1961.

This paper constituting the 1960 William M. Murray lecture to the Society for Experimental Stress Analysis, is a review of an area in which the author has distinguished himself. The main thesis of the paper emphasizes the importance of the stress distribution in the region of the maximum stress in understanding the strength behavior of structural numbers under service conditions. A discussion of the effective use of surface hardening illustrates this point in simple, yet effective terms. An illuminating presentation of conditions for crack formation and propagation in notches numbers should prove of value to design engineers.

286.

Pfeiffer, A., "Theory of Corrugated Diaphragms for Pressure-Measuring Instruments", Rev. Sci. Inst., 18, pp 660-664, September 1947.

A hypothetical model for the distribution of stress in diaphragms is discussed. It is constructed of members in series, with each consisting of one flexural and one tension spring acting in parallel. This hypothetical model leads to a correlation between pressure P acting on the diaphragm, corresponding deflection of the diaphragm h, effective diameter 2r, sheet thickness d, and "plate modulus" F, as a measure of elasticity. This formula checks well with the data for the author's test material as well as with other experimental results on diaphragms with pressure-proportional deflection. The probable relation of the separate terms of the formula to definite annular zones of the diaphragm as well as its applicability to diaphragms with other than pressure-proportional deflection are discussed.

287.

Pike, E. W., and Gibbs, N. E., "Study on Aneroid Capsules", J. Appl. Phys., 19, pp 106-108, January 1948.

The analysis of aneroid capsule performance by the expansion of the observed pressure-deflection curve in Gram summation-orthogonal polynomials is illustrated on a series of 15 runs on 5 typical capsules. All of the deflection curves examined contained significant cubic and quartic terms while a few showed fifth-order terms. These high order terms are very unstable in magnitude and sign for successive deflections of the same capsule, and this accounts for the very complex hysteresis curves which have been observed. The relationship of these high order terms in the deflection characteristic to the accuracy and cost of precise aneroid barometers is brought out, and it is suggested that barometric systems free of elastic redundancies must be devised if accurate barometers for radiosondes and similar instruments are to be mass produced.

288.

Pohl, S. W., "Compatibility of Bellows Material With N_2O_4 and MMH", Douglas Aircraft MSSD Final Rept. ML64-151, 1964.

N_2O_4 exposure tests were run on AM 350-SCT bellows samples at 70 F and 160 F with 0 and 1 percent water added. Three samples each and three stress levels (above yield, below yield, and no stress) were included at each condition. The exposure tests for 2-week, 4-week, 8-week, 12-week, and 24-week tests are reported. Comparison tests have been included on AM 350-H and SS 347-A.

289.

Pollard, F. H., "Research Investigation of Hydraulic Pulsation Concepts", Republic Aviation Corp., February 29, 1964 (AD 431304).

This is the Fourth Quarterly Progress Report under Contract AF 33(656)-10622. During this period, system efficiency and transmission-line-loss methods were derived. Experimental system efficiency and line-loss data were secured from the miniaturized system. Designs of a diaphragm- and mechanical-type transformer were studied. System-failure and functional-effect analyses were made. Also, a preliminary glossary of terms peculiar to pulsating hydraulics was compiled.

290.

Pomey, G., and Grumbach, M., "Some Relationships Between Coefficients of Anisotropy, Work Hardening, and Deep-Drawing Tests", Rev. de Met., 61, October 1964 (in French).

Tests were made on extra mild steels, light alloys, and other materials which can be found in the form of sheet or strip.

291.

Porter, R. N., and Stanford, H. B., "Propellant Expulsion in Unmanned Spacecraft", SAE-ASME Paper 868B, April 27-30, 1964.

Bladders, diaphragms, and pistons used for the positive expulsion of earth-storable liquid rocket propellants are discussed in general terms. The history of JPL's work on these devices is reviewed as a background to the current progress. A detailed account of the development and use of bladders in Ranger and Mariner spacecraft is presented. The final section describes an advanced development program aimed at providing technology for future spacecraft.

292.

"Pressure Measuring Techniques Feasibility Evaluation", Instrumentation Div. of Gulton Industries, Inc., 132 pp, July 1960-November 1961.

Based upon the results obtained during an investigation into the fabrication of a pressure transducer to operate in high-temperature environments, the variable coupling pickoff approach appears to have an upper practical temperature limit of approximately 1000 F. Although transducers were constructed which operated to 1500 F, the data obtained above 1000 F were erratic and showed insufficient promise to extend the usable range above this temperature at this time. Should the state of the materials art advance in the near future, particularly with respect to ceramic cements, film insulations, stronger ductile metals and temperature-compensation components, then the feasibility of constructing a transducer using the variable coupling pickoff and diaphragm pressure-element technique will be considerably enhanced.

293.

"Pressure Transducing and Instrumentation Techniques", I, Bk I, Giannini Controls Corp., Duarte, Calif., August 1, 1960 (AD 251111).

An engineering study and evaluation of pressure transducing techniques and related transmitting and indicating system techniques is presented in two volumes of four books. Vol. I, consisting of Bks 1, 2, and 3, gives a general introduction and covers the current state of the art. Vol. II includes improvements, miniaturization and new techniques, in addition to a reference section. Covered are pressure ranges from 50 to 5000 psi and temperature ranges from -300 to 1000 F for rocket fuels and oxidizers, aircraft fuels, exhaust products, engine lubricants, and hydraulic fluids. Transducers, converting pressure into displacement, and transmitters, converting transducer displacement into a suitable electrical voltage, are covered individually and in combination as to materials, design considerations, manufacturing, performance, and limitations. Information on size, weight, input vs output characteristics, accuracy, repea' `ility, reliability, and life is given. Discussed are effects of and compen   .on for corrosive media, temperature, vibration, acceleration shock, and nuclear r: .iation. Applications, recommended usage, and performance improvements, advantages and disadvantages, are cited. Much of the information is presented in the form of illustrations and tabulated data.

294.

"Production of High-Strength Bellows", Metal Ind., 97 (21), pp 423-424, Nov. 18, 1960.

Brief descriptions are given of techniques of making bellows of Monel and stainless steel.

295.

Radkowski, P. P, et al., "Numerical Analysis of Equations of Thin Shells of Revolution", Am. Rocket Soc. J., 32, pp 36-41, 1962.

A numerical analysis is given for the solution of the general equations of thin shells of revolution subjected to rotationally symmetric pressure and temperature distributions. The basic differential equations are in a very general form, which permits the geometry of the shells considered to be specified by discrete data points. The analysis determines elastic stresses, strains, and displacements for multilayer and multisectional shells of revolution. Surface loads, temperatures, thicknesses, and material properties may vary arbitrarily in the meridional direction. Temperatures and material properties can also vary through the thickness. The solution is obtained by direct computation using a numerical method that employs two by two coefficient matrices and hence avoids the problems of slow convergence. The solution has been programmed in a semi-algebraic language that can be used on most high-speed computers. Comparisons of numerical solutions to known exact and approximate solutions of the thin-shell equations are made to demonstrate the accuracy of this method.

296.

Ralph M. Parsons Co., Test Report, "Results, Prequalification Test for Flexible Metal, Wire-Reinforced Hose", February 23, 1961 (AD 283712).

Tests of 1/2, 1-1/2, and 4-inch flexible-metal hose assemblies included visual examination, proof pressure (150 psig), maximum deflection cycling (10 cycles), and flow (222 gpm).

297.

Raymond, R. H., "Proper Pre-Weld Practice Produces Better Aluminum Cryogenic Bellows", Mod. Metals, 19, p 46, November 1963.

The newer weldable alloys enhance aluminum's competitive position for cryogenic bellows and ducting, but rigorous control of fabrication - especially welding - is needed.

298.

Redner, S., and Zandman, F., "Experimental Stress Analysis", Ind. Res., 7 (5), pp 67-72, May 1965.

With the availability of easily worked photoelastic plastics and coatings and efficient and large beams of polarized light, in addition to the development of various types of strain-measuring devices and Moire-effect techniques, experimental analysis can be used to obtain a quick and thorough understanding of the stress behavior of a structure.

299.

Reissner, E., "On Stresses and Deformations in Toroidal Shells of Circular Cross Section Which are Acted Upon by Uniform Normal Pressure", Quart. Appl. Math., 21 (3), pp 177-187, October 1963.

The present object is a more general approach to the problem through a system of differential equations which contain both the equations of the linear-bending theory and of the nonlinear-membrane theory as limiting cases, and which remains applicable in the transition region when both linear bending and nonlinear membrane action have to be considered simultaneously. Specifically, the objective is to determine the ranges of values of suitable nondimensional parameters for which linear bending theory and nonlinear-membrane theory are appropriate, and also the ranges of these parameters for which the problem belongs to the transition region between the two limiting forms of the theory. Derivation of the differential equations which govern the problem in all three ranges is accomplished through appropriate specialization of a general system of differential equations for finite symmetrical deflections of shells of revolution which has previously been given by the author.

300.

Reissner, E., "On the Theory of Thin Elastic Shells", H. Reissner Anniversary Volume, pp 231-247, 1949.

This paper is concerned with the subject of rotationally symmetric deformations of thin elastic shells of revolution. First a self-contained formulation of the problem of finite symmetrical deflections of shells of revolution is given. From this the equations of the small-deflection (linearized) theory are obtained by specialization. From the general equations of the small-deflection theory in a systematic manner a simplified system of equations is obtained which applies for shallow shells. It is shown that the solution of this system of equations can be expressed in terms of Bessel functions for the entire class of paraboloidal shells of constant thickness. This generalizes known results for the case of a shallow spherical shell for which the meridian curve is equivalent to a second-degree parabola. It is also shown that the solution can be given in terms of elementary functions for a class of shallow shells with varying thickness, such that the problem of conical shells with linearly varying thickness is included as a special case.

301.

Reissner, E., "Rotationally Symmetric Problems in the Theory of Thin Elastic Shells", Proc. of the Third U.S. Natl. Congress of Appl. Mech., ASME, 1958.

General problems in the theory of thin elastic shells require the determination of stresses and deformations as a function of two space coordinates. Rotationally symmetric problems have the property that stresses and deformations depend on one space coordinate only. This means that, for time-independent problems, one is concerned with ordinary differential equations rather than with partial differential

equations. This paper reviews a number of problems and solutions in the field of rotationally symmetric deformations of thin shells, all of them dealing with shells of revolution which are the most natural source of such problems. Consideration is given to linear and nonlinear problems of the statics of shells of revolution, with particular emphasis on asymptotic solutions and edge effects. In addition, the problem of bending of pressurized curved tubes is formulated in considerable generality.

302.

Rekate, H. L., and Schwartz, J. I., "Behavior Study of a Curtiss-Wright Snorkel Flexible Exhaust Connection for Submarine Application", U.S. Navy Marine Eng. Lab, November 13, 1963 (AD 423023).

The vibration endurance and shock characteristics of a flexible connection for a Curtiss-Wright engine exhause system were investigated and found to be satisfactory. From previous investigations, it had been found that stainless steel is a material for this flexible exhaust; Inconel should be considered. This report presents a proposed method for evaluation of future designs of flexible connections.

303.

Rothfuss, N. L., et al., "Design and Application of Metallic Flexures for Equipment With Specific Life Requirements", SAE-ASME Paper 871A, April 27-30, 1964.

This paper treats the design, application, variations, and combinations of four basic types of metallic flexures which do not have sliding or rolling load carrying contacting surfaces - flat springs, round bars, curved beams, and diaphragms. Flat springs develop into flexural pivots, used to replace conventional oscillating bearings in equipment such as gyros, gimbal rings, and linkages of all types. Round bars develop into torsion bars to replace conventional bearings with very limited torsional movement and quill shafts used as flexible shafts with limited angular movement. Curved beams develop into the gimbal ring and the curved beam lattice. Diaphragms develop into specially shaped contoured diaphragms for torsional load carrying capability at high angular misalignments. The basic kinematics, the equations for determining their approximate size, and many new applications are also discussed.

304.

Salzmann, F., "Compliance of Corrugated Expansion Joints", 127 (11), pp 127-130, March 1946 (Translated from Schweizerische Bauzeitung).

In this paper the compliance of corrugated pipes under the influence of forces in the pipe axis direction is studied, with full account taken of hoop stress influence. Corrugated shapes composed of straight lines and arcs are studied; the most favorable conditions with regard to compliance are found. Subsequently the behavior of bending loading is shown for individual cases.

305.

"Seamless Metal Bellows - Behave as Spring-Loaded, Frictionless Pistons When Subjected to Pressure", Design News, 14 (16) pp 18-19, August 1959.

The characteristics and applications of seamless metallic bellows are described briefly.

306.

Seibel, M.P.L., "Differential Pressure Gage", Electromechanical Design, 7 (9), pp 64-65, September 1963.

The pressure sensing element is a spring-loaded bellows located in the pressure housing. High pressure admitted through the high-pressure port acts upon the outside of the bellows, while lower pressure admitted through other ports acts upon the inside of the bellows. The bellows is compressed by the effect of the net pressure difference but the absolute-pressure level has no effect upon the bellows. Compression of the bellows moves a magnet along a bore inside the pressure housing and this movement is picked up by two follower magnets, outside the pressure housing attached to a light pivoted yoke carrying the pointer.

307.

Seide, P., "The Effect of Pressure on the Bending Characteristics of an Actuator System", ASME Trans. 82, pp 429-437, 1960.

The effect of internal or external pressure on the bending of a cantilevered bellows, the movable end of which is permitted only to rotate about a fixed point on the longitudinal axis of the beam, is investigated. It is found that the bending characteristics of the system vary considerably with changes in pressure and pivot-point location and that instability of the system may occur. The experimental results given tend to confirm the behavior predicted by the theory.

308.

Sepotoski, W. K., et al., "A Digital Computer Program for the General Axially Symmetric Thin-Shell Problem", ASME Trans., 84, pp 655-661, 1962.

This paper describes the development of a general computer program to handle arbitrary thin shells of revolution subject to radially symmetric loading or temperature variation. An elimination method is used to solve the set of difference equations obtained from the basic differential equations; a feature of the method is that "edge effect" difficulties that can arise with conventional differential-equation routines are avoided. The program is quite flexible and permits discontinuities in shell geometry or loading. The results of applying the program to several classical problems of known solution are given. These results permit the examination of computational accuracy for varying boundary conditions and mesh sizes. Finally, some program solutions of unconventional problems are presented.

309.

Serensen, S. V., and Snneiderovich, R. M., "On the Investigation of the Stress-State and Strength for Elastic-Plastic Cyclic Deformations", Ian OTN SSSR, Mekh. i Mash., 4, pp 136-140, 1961 (in Russian).

This paper considers the dependence of the stress-strain behavior of a material on the number of cycles through which the specimen is deformed.

310.

Shawki, G.S.A., "Assessing Deep-Drawing Qualities of Sheet, I, Stretch-Forming and Wedge-Drawing Tests", Sheet Metal Ind., 42, pp 363-368, May 1965.

This paper presents a critical review of the methods of assessing deep-drawing qualities of sheet metal developed during the last 50 years, and discusses stretch-forming, wedge-drawing, deep-drawing, and combined simulative tests.

311.

Shield, R. T., and Drucker, D. C., "Limit Strength of Thin Walled Pressure Vessels With an ASME Standard Torispherical Head", Proc. of the Third U.S. Natl. Congress of Appl. Mech., ASME, pp 665-667, 1958.

Results are presented for the maximum pressure which an unfired vessel with an ASME standard torispherical head can withstand before appreciable plastic deformation will occur. The effect of flanges on strength is considered. Although the procedures outlined permit variation of pressure in the axial direction to be taken into account fully, for convenience the calculations are based upon the assumption of uniform interior pressure. Work-hardening is not of much significance for thin-walled vessels of the usual steels and is ignored. A comparison is made with the ASME Code for unfired pressure vessels. A real danger is pointed out which is especially important in connection with brittle fracture at low temperature.

312.

Smith, A. H., and MacDonald, W. R., "Aliasing Errors in A. C. Bridge Transducer Measurements", Royal Aircraft Establishment, Farnborough, 9 pp, December 1963 (AD 438804).

A pressure-sensing element (usually a diaphragm, bellows or capsule) can, under mechanical excitation, resonate at a frequency considerably higher than the cut-off frequency of the acoustical system controlling the response to pressure changes. Troubles of this nature can be avoided by supporting the transducer on suitable anti-vibration mounts.

313.

    Smith, E. M., "Analysis of Creep in Cylinders, Spheres, and Thin Discs", J. Mech. Eng. Sci., 7 (1), pp 82-92, 1965.

    A method of analyzing the creep behavior of cylinders, spheres, and thin discs is described in which the effects of time variation of the environmental conditions of temperature, pressure, rotational speed and internal heat generation may be accommodated. Deformation is considered as a series of steps each consisting of a short period of steady state creep followed by instantaneous stress readjustment to resatisfy the equations of equilibrium and compatibility. The relationships for stress readjustment can be written down once for all, since they are independent of the type of creep law used and of the length of time interval taken. The simultaneous solution of these relationships is presented in a form suitable for incorporation in computer programs.

314.

Standards of the Expansion Joint Manufacturers Association, 2nd Edition, 1962, New York.

    The previous edition, published in 1958, was the first attempt to set forth recommended standards, consistent with safety and service conditions, for the mechanical design and application of all the various types of Packless Expansion Joints, regardless of bellows design and construction. The major objectives of this first edition were to clarify the conflicting and ambiguous terminology then in use in the industry and to establish and maintain high standards of quality that would ensure Expansion-Joint users of long-lived, trouble-free equipment. Since this second edition was greatly expanded in scope, particularly with respect to complex piping configurations involving lateral deflection and angular rotation, it was hoped that its use as a specification medium would increase.

315.

    Stange, K., "Strains in an Annularly Corrugated Diaphragm", Ing.-Archiv, 2, pp 47-91, 1931 (in German).

    This paper gives an approximate solution of a toroidal segment in terms of a power series in the angle ϕ between the axis of symmetry and the normal to the shell. It is assumed that $\sin \phi < 1$ so that the solution is only applicable to torcidal segments of the type found in diaphragms.

316.

    Stedman, C. K., "The Characteristics of Flat Annular Diaphragms", Statham Laboratories Instrument Notes, 4 pp, January 1957.

    A good deal of information, both theoretical and experimental, concerning flat-plate diaphragms has been published. But it is somewhat scattered, and mostly pertains to diaphragms without central reinforcement. For this reason the equations for the rigid annulus, which is a considerably more versatile form, are presented in this issue of Instrument Notes with the thought that its advantages might be more widely exploited if design information were made readily available.

317.

Stedman, G. E., "Metal Bellows Involve Unusual Metalworking Operations in Their Manufacturing", Steel, <u>114</u>, pp 116-118, April 3, 1944.

This article describes processes for making hydraulic and spin-rolled metal bellows.

318.

Steele, C. R., "Shells of Revolution With Edge Loads of Rapid Circumferential Variation", (J. Appl. Mech.) ASME Trans., <u>84</u>, pp 701-707, 1962.

After an investigation of membrane theory, solutions to the general equations for a thin shell of revolution of arbitrary meridian are obtained for rapidly varying sinusoidal edge loading. The solutions from membrane theory are shown to be valid for shells near spherical shape but can give quite misleading results, particularly for shells of negative curvature. The "edge-effect" solutions also are shown to become significantly modified for the high harmonics.

319.

Steele, C. R., and Hartung, R. F., "Symmetric Loading of Orthotropic Shells of Revolution", Lockheed Missiles Tech. Rept., March 1964.

In this report, the problem of determining the stresses and deformations in a thin homogeneous, orthotropic shell of revolution under the action of axi-symmetric loads is reduced to the solution of a single inhomogeneous second-order linear differential equation with a complex dependent variable. Asymptotic solutions are obtained which are uniformly valid in both the steep and shallow regions of the dome-shaped shell. The complementary, or "edge-effect" solutions are expressed in terms of Thomson's functions of a non-integer order. The order depends both on the shape of the meridian curve at the apex of the shell and on the ratio of the elastic moduli. The parti-cular solution is found in terms of an appropriate linear combination of Lommel's function and Thomson's functions. This particular solution is equiva-lent to the well-known "membrane" solution in the steep portion of the shell, but in the shallow portion gives significant bending stresses. The particular and complementary solutions are used to investigate the behavior of orthotropic pressure vessels with rigid rings clamped to the edges.

320.

Steele, C. R., "Toroidal Shells With Nonsymmetric Loading", Thesis, Stanford University, 96 pp, 1960.

The eighth-order partial differential equations for a shell of revolution reduce for sinusoidal edge loading to an eighth-order ordinary differential system - three simultaneous equations. These proved unwieldy for the toroid and so were reduced in this work to one nonhomogeneous integral-differential equation which can be further modified to a form quite similar, except for the integral, to the fourth-order formulation of the axially symmetric problem treated previously. Asymptotic forms of the four solutions of the homogeneous

equation for all harmonics were found to coincide with the damped oscillatory "bending" or "edge-effect" solutions of the symmetric problem because the harmonic index n did not appear in the terms that proved to be important. Solutions of the nonhomogeneous equation coincide with membrane and inextensional deformation solutions in the nonshallow regions of the shell, so these have been investigated and their computation requirements reduced to the numerical solution of two simple equations and some numerical integration. Then using a generalization of the technique of R. A. Clark, asymptotic solutions of the nonhomogeneous equations were found in terms of the membrane and inextentional deformation solutions and the function T used by Clark. The results of this investigation are limited to thin shells and slowly varying loads. Criteria are given for both limitations.

321.

Stein, M., and McElman, J. A., "Buckling of Segments of Toroidal Shells", AIAA 2nd Aerospace Sci. Meeting, January 25-27, 1965 (AIAA Paper No. 65-77).

Nonlinear differential equations of equilibrium and buckling equations are derived for segments of toroidal shells near the equator and for segments near the crown. The equations are derived for shallow-shell segments by including appropriate prescribed initial displacements in the nonlinear, flat plate, strain-displacement equations and by varying the total potential energy of the system. Closed form solutions to the buckling equations are obtained for simply supported segments near the equator having either positive or negative Gaussian curvature under pressure loading with various inplane support conditions. Results are presented in the form of charts showing buckling coefficients as a function of a curvature parameter associated with the girth of the shell and a parameter associated with the ratio of principal curvatures. In many instances the results indicate significant deviations in buckling stress for the toroidal shells over the buckling stress for the corresponding circular cylindrical shell under similar loading and support conditions.

322.

Stevenson, F. D., and Wicks, C. E., "A Metal Diaphragm Apparatus for Measuring Vapor Pressures, Vapor Pressure of Arsenic (III) Oxide", U.S. Dept. of Interior, Bureau of Mines, Rept. of Investigations 6212, 1963 (N63-14255).

A metal diaphragm pressure relay system was constructed to measure vapor pressures of the metal halides, oxyhalides, and other substances at temperatures up to 700 or 800 C.

323.

Stippes, M, and Beckett, R. E., "Symmetrically Loaded Circular Plates", J. Franklin Inst., 257, pp 465-479, June 1954.

A solution is derived for the nonlinear deflection of a circular plate which the authors feel is somewhat more general than Way's solution.

324.

Stricklin, J. A., et al., "Large Elastic, Plastic, and Creep Deflections of Beams and Axisymmetric Shells", AIAA Journal, 2 (9), pp 1613-1620, September 1964.

A numerical method is presented for analyzing large deflections of curved beams and large axisymmetric deflections of shells of revolution. The governing equations that are in finite-difference form are solved by a Newton-Raphson iteration procedure. The plastic stress-strain relations are determined by assuming three independent slip planes that are the planes of maximum shear stresses. The stress-strain relation along each slip plane is assumed to be linearly strain hardening. This plasticity model gives piecewise-linear plasticity relations with determinate coefficients. For snap buckling problems, the so-called upper critical load is determined by introducing an artificial spring opposite to the applied load. The true load is then the difference between the applied load and the reaction of the spring. The important mathematical consequence of introducing the spring is to yield a single-valued load-deflection curve, thus allowing the critical loads to be determined. The method is applied to several problems including low arches, circular rings, shallow and deep spherical shells under elastic-plastic deformations, and a shallow arch under creep deformation.

325.

Stroner, P. R., "Structural Stability of Toroidal Shells", Lockheed Missiles and Space Company, June 1963 (AD 423823).

The toroidal shape is of particular interest in space applications as an optimum design for space vehicle liquid storage containers and for inflatable or collapsible structures. Torus designs have also been used by nuclear physicists to confine atomic fusion reactions in particle accelerators. Both linear and nonlinear methods of stress analysis have been developed to study the structural stability of these shells; however, no reference to buckling behavior of toroids was located in this review of the literature covering the period January 1948 to June 1963. A subject index is included.

326.

Sutton, G. P., "Charts for Circular Diaphragm Design; Reference Book Sheet", Prod. Eng., 18, pp 167, 169, January 1947.

Charts which are presented provide design information for circular thin diaphragms, of uniform thickness and with fixed edges, subjected to a uniformly distributed load. Chart A is used to determine stresses and Chart B is used to determine deflections for a given material and given dimensions.

__327.__

Swindeman, R. W., and Douglas, D. A., "The Failure of Structural Metals Subjected to Strain-Cycling Conditions", ASME Paper No. 58-A-198, 1958.

Data showing the isothermal strain-cycling capacity of three metals, Inconel, Hastelloy B, and beryllium are presented. It is noted that at frequencies of 0.5 cycle per min. the data satisfied an equation of the form $N^\alpha \epsilon_p = K$, where N is the number of cycles to failure, ϵ_p is the plastic strain per cycle, and α and K are constants whose values depend on the material and test conditions. Data on Inconel are given to establish the effect of grain size, specimen geometry, temperature, and frequency. It is found that, at temperatures above 1300 F, grain size and frequency exert a pronounced effect on the rupture life. Fine-grained metal survives more cycles before failure than coarse-grained material. Long time cycles shorten the number of cycles to failure when the strain per cycle is low. Thermal-strain-cycling data for Inconel are compared to strain-cycling data at the same mean temperature. Good correlation is found to exist between the two types of tests.

__328.__

Tao, L. N., "On Toroidal Shells", J. Math. Phys., _38_, pp 130-134, July 1959.

Since the classical work of H. Reissner, the determination of the elastic deformation of shells of revolution under axisymmetric loading has been the subject of numerous investigations. For toroidal shells the problem has been studied by Wissler and Chang using power-series solutions, and by Chang and Clark by means of asymptotic integrations. It is the purpose of this note to establish the solution in closed form, expressed in terms of a comparatively unknown function, the Heun function. Though the present solution is still in the form of a power series, it has some advantages over the previous solutions obtained by Wissler and Chang.

__329.__

Tavernelli, J. F., and Coffin, L. F., Jr., "Experimental Support for Generalized Equation Predicting Low Cycle Fatigue", Trans. ASME 84D, _4_, pp 533-541, December 1962.

A simple equation proposed by Langer and based on relationships found by Coffin has been compared with measured values from 12 published fatigue tests with different steels, copper, nickel, titanium, and aluminum alloys. Equation gives stress amplitude of low-cycle fatigue $S = 1/2 E c N^{-1/2} + S_e$ where S_e is endurance limit, E modulus of elasticity, N cycles to failure and $c = 1/2 \epsilon_f = -1/2 \ln (A/A_o)$, where ϵ_f is fracture ductility (from static tensile test), A_o initial area, A final area. In most cases equation gives conservative values for low cycles, due to basing constant c on static fracture ductility.

__330.__

"Test System Analysis Study for Propulsion Research Environmental Chamber", Research Management Assoc., November 23, 1963 (AD 421020).

The feasibility of developing a facility for the testing of rocket propulsion systems employing high energy, toxic, and hypergolic propellants under simulated

space environmental conditions has been established through analytical studies. Propellant storage and main propulsion unit firing testing can be achieved with a combination of double-walled vacuum chamber and an exhauster system separated by an impermeable flexible metallic interface that allows full gimballing of the rocket motor.

331.
Thompson, L. M., "Welded Metal Bellows, A Reliable Positive Expulsion Device for Liquid Propellants", AIAA Paper No. 64-264, Bell Aerosystems Co.

The potential of the welded metal bellows device was explored during a design study program by Bell Aerosystems Company in March 1963 for NASA, under contract NAS7-149. This program was conducted to evaluate metallic positive expulsion devices and to select the device having the greatest potential for manned application. In the initial phase of this program, an industry-wide survey was conducted to ascertain the state of the art in development of all types of expulsion devices. The survey also included a review of the present status of our technology, where it applied, and the monitoring of programs currently in progress at Bell Aerosystems Company. Phase I of NAS7-149 was completed with a definitive design study and parametric analysis of the three most promising metallic devices for a cylindrical envelope: the piston, metal bladder, and welded metal bellows. The results of this parametric analysis demonstrated the superior potential of the metal bellows and this device was selected for a comprehensive design study in Phase II.

332.
Thompson, A. I., "Rupture-Proof Bellows-Type Orifice Meters", Instruments, 25 (11), pp 1593-1596, November 1952.

Important factors associated with rupture-proof dual-bellows flowmeters include bellows construction, temperature compensation, range springs, ease of servicing, freedom from over-range damage, high sensitivity, simple installation, and applicability over wide ranges of differential and static pressures.

333.
Thomsen, E. G., Yang, C. T., and Kobayashi, S., Mechanics of Plastic Deformation in Metal Processing, Macmillan Co., New York, 1965.

The authors discuss the presently known methods of solution to some of the problems of metal forming obtained from principles of plasticity. Comparison of solutions with experimental data has been made where possible. Subjects covered include buckling, necking, fracture mechanics, and slip-line solutions as applied to the processes of forging, extruding of solid and hollow forms, coining, rolling, spinning, machining, and drawing of wire and tubing. Much recent information is presented that is not otherwise easily accessible.

334.

Thomson, J. H., "Torsion Bar Pressure Transducer", Electromechanical Design, 8 (6), pp 46-50, June 1964.

The torsion-bar pressure transducer is quite simple. Pressure applied at the pressure tap applies a force on the arm which twists the torsion bar slightly. The evacuated bellows provide an absolute reference and a mechanical balance. Bellows of the best available welded type made of AMS 350 steel were selected for inherent uniformity of the effective area, good high-temperature characteristics, and good spring characteristics.

335.

Timms, R. J., "Analysis of Toroidal Shells", Thesis, Northwestern University, 1953.

This dissertation gives a generalization of Clark's asymptotic solution of toroidal shells to make the results to a wider variety of cases. An attempt was made to develop simple design formulas to be used under specific conditions.

336.

Toles, G. E., "Water-Formed Big Expansion Joint for ASCL Reactor", Design Eng., 9 (8), p 41, August 1963.

An expansion joint was made of 304L stainless steel, 1/4 inch thick. The diameter of each end was 104 inches. It was decided to have the expansion joint hydraulically formed rather than roll-formed (which would have been far simpler) because the former method eliminated surface blemishes likely to result from roll-forming. It also was considered desirable in order to achieve greater uniformity of metal.

337.

Tumarkin, S. A., "Analysis of Symmetrically Loaded Toroidal Shells With the Aid of Trigonometrical Series", Prikl. Mat. i Mekh., 16 (5), pp 569-574, 1952 (in Russian).

The toroidal-bellows problem is solved in terms of trigonometric series in the angle ϕ between the normal and the axis of symmetry. A toroidal bellows with axial loads is solved.

338.

Tumarkin, S. A., "Asymptotic Solution of a Linear Nonhomogeneous Second Order Differential Equation With a Transition Point and its Application to the Computations of Toroidal Shells and Propeller Blades", Appl. Math. Mech., 23, pp 1549-1565, 1959.

This is a theoretical derivation of the asymptotic solution for the toroidal-shell equations. Estimates are obtained for the errors in the solutions. One solution is obtained for a toroidal shell and compared with Clark's

first results. Tusarkin did not seem to be aware of some of Clark's later papers which contained the same results that were given in this paper.

339.

Turner, C. X., "Stress and Deflection Studies of Flat-Plate and Toroidal Expansion Bellows, Subjected to Axial, Eccentric, or Internal Pressure Loading", J. Mech. Eng. Sci., 1 (2), pp 130-143, September 1959.

Tests in axial compression, eccentric (hinge) loading and internal pressure are described for corrugated-pipe and flat-plate bellows. Strain gage surveys and deflection readings were made for each test. A recently developed theory for the small elastic deflection of toroidal elements is briefly described and its application to a wide range of bellows shapes and loadings is discussed. For some flat-plate bellows, where the depth of convolution is much smaller than the over-all radius of the bellows, an approximate theory neglecting circumferential effects is possible, and comparison is made between this approximate and the more exact theory. Both theory and experiment show that the location of the maximum stresses depends markedly upon the proportions of the bellows. General bellows design and construction problems are examined in the light of the stresses likely to be caused by actual service conditions of operation.

340.

Turner, C. E., "Study of the Symmetric Elastic Loading of Some Shells of Revolution With Special Reference to Toroidal Elements", J. Mech. Eng. Sci., 1 (2) pp 113-129, September 1959.

The governing equations for the elastic behavior of axisymmetrically loaded thin elastic shells of revolution are derived and applied particularly to toroidal shells where the radius of revolution is much larger than the radius of ring cross-section. It is shown that under these conditions the approximate equations are a special case of the Mathieu type. Some solutions have recently been tabulated enabling the theory to be applied to structures such as toroidal pressure-vessel heads, expansion bellows and similar shapes. Comparison is made with an approximate series solution of the same equations.

341.

Turner, C. E., and Ford, H., "Stress and Deflection Studies of Pipeline Expansion Bellows", Proc. Inst. of Mech. Eng., 171 (15), pp 526-552, 1957.

In the design of pipelines for high-temperature service, allowance has to be made for the thermal expansion of the heated pipe. One particular aspect of this problem is the use of bellows expansion joints which, particularly on board ship, can transmit the pipe movements through bulkheads while providing a watertight flexible anchorage. An approximate theory has been developed for the compression of a bellows, the convolutions of which have a cross section formed by circular arcs subtending any semi-angle α. Numerical results

have been calculated for the two cases $\alpha = \pi/2$ and $\alpha = 3\pi/4$. Experiments have been carried out on six bellows, four corrugated-pipe type $\alpha = \pi/2$, one S-type $\alpha = 3\pi/4$, and one flat-plate type which was not analyzed theoretically. Deflection and resistance strain-gage readings were taken on each bellows, and reasonable agreement was found between the theoretical and experimental results for the five bellows in which these could be compared. It has been found that for certain design conditions optimum relationships exist between bore, wall thickness, and radius of convolution for the maximum flexibility. Stress intensification and flexibility factors have been calculated to cover a range of bellows proportions.

342.

Turner, E. M., "Design Parameters for Elliptical Toroidal Pressure Vessels", Aerospace Eng., 21 (11), pp 33-38, November 1962.

A presentation is made of a design parameter curve for elliptical toroidal pressure vessels in nondimensional form, relating the radius of rotation about an axis to the ratio of the semiaxes of the ellipse to maintain tension throughout the pressure vessel.

343.

Tweeddale, J. G., The Mechanical Properties of Metals, George Allen and Unwin, Ltd., London, 1964.

This book covers the field of the assessment of mechanical properties of engineering materials relative to design and manufacture, theoretical and practical limitations on properties, difficulties in analyzing and recording properties, and problems associated with the testing of materials and types of testing machines.

344.

Vail, D. B., "Determination of the Natural Frequencies of Vibration in the Breeze Bellows", Knolls Atomic Power Lab. Rept. KAPL-M-DBV-4, March 4, 1954.

The investigation of the resonant frequencies of the Breeze bellows which were used in the SIR Mark A 8-in. stop valves was continued. The effects of the exciting displacements and pressure differentials upon the fundamental and harmonic resonant frequencies of the extended and compressed bellows were observed. Also, the effects of transverse restraint and of fluid in the bellows upon the resonant frequencies were observed.

93

345.

Van der Pyl, L. M., "Bibliography on Diaphragms and Aneroids", ASME Paper 60-WA-122, 1960.

A Literative Survey Committee was created by the Research Diaphragm Sub-committee of the Research Committee on Mechanical Pressure Elements to accumu-late a list of the outstanding papers and literature on "Diaphragms and Aneroids". This list was to include many of the papers listed in the biblio-graphy on "Diaphragms and Aneroids" published previously (ASME Paper No. 55-A-180 by G. H. Lee and L. M. Van der Pyl) with the addition of some missing papers and some later papers. The 171 abstracts offer an account of the available literature in this field. The abstracts are arranged alphabeti-cally under the name of the author or senior author. A chronological index is also given.

346.

Volkov, A. N., "Contact Problem of a Combined Toroidal Shell With Ring Plates", Inzh. Zh., 3 (2), pp 331-336, 1963 (N64-28483) (translation).

This work performs an analysis of a system of equations expressing conditions for contact of an annular plate with a toroidal shell and describes boundary conditions in connection with the design of corrugated shells for bellows.

347.

Volkov, A. N., "Determination of the Axial Rigidity of Corrugated Shells With Reference to Calculation of Bellows", Inzh. Zh., 2 (2), pp 368-372, 1963 (in Russian).

This note presents a simple method for predicting the longitudinal rigidity of a bellows in terms of a strip of unit width by the energy method of Castigliano (beam theory).

348.

Volkov, A. N., "Investigations of the Stressed State of Toroidal Shells", Inzh. Zh., 2 (4), pp 312-320, 1962 (in Russian).

This paper investigates the stress-strain state of toroidal shells using the asymptotic solutions of Novozhilov. The effect of the singularity at $\phi = 0$ is discussed.

349.

Voloshin, A. A., "Flexibility and Strength of Convoluted Bellows of Pipelines", Vestn. Mashinostr., 4, pp 12-16, 1958 (in Russian).

In pipelines with an internal pressure of 2 to 4 kg/cm^2, convoluted bellows are widely used. The typical design is shown of a bellows with an internal hinge

coupler eliminating the relative axial displacement of the flanges. In its plane of motion the coupler permits a linear and angular displacement of the flanges of the bellows. Spring rates for these types of motion are determined experimentally for three bellows.

350.

Wahl, A. M., "Recent Research on Flat Diaphragms and Circular Plates With Particular Reference to Instrument Applications", ASME Trans., 79 (1), pp 83-87, January 1957.

A discussion and literature survey of recent theoretical and experimental developments relating to flat plates and diaphragms is given, with particular reference to applications in pressure-measuring instruments. Developments discussed include: Effects of large deflections; initially buckled diaphragms; plates subject to plastic flow; analysis of temperature and acceleration effects in diaphragms for pressure measurement. Some discussion of instruments utilizing flat or nearly flat diaphragms is given and an attempt is made to indicate possible fruitful avenues of future research in the diaphragm field.

351.

Walter, L., "Metallic Flexible Seamless Bellows", Mass Prod., 25 (11), pp 50-59, November 1949.

Metallic seamless bellows are design elements used in many types of apparatus, instruments, and plant equipment. Here are a few well-known applications using their elasticity in longitudinal axis: power elements for industrial thermostats, cooling water or radiator thermostats for motor cars, pressure reducing devices, packless glands, packless shaft seals, expansion joints for pipes, flexible couplings, noise dampers, packless valves, special piston-less pumps, etc. These applications may take the form of either a piston and cylinder, frictionless and hermetically sealed, or of a flexible closure.

352.

Walter, L., "The Use of Flexible Metal Bellows as Design Elements", Part 1, 62 (2) February 1951, Part 2, 62 (6), June 1951, Can. Mach. and Manuf. News.

A general discussion is given in both articles of the design and application of formed bellows.

353.

Walter, L., "Use of Seamless Metallic Bellows in Design", Eng. Mater. and Design, 3 (10), pp 618-621, October 1960.

The seamless metallic bellows allows the designer to combine the characteristics of the helical spring and the semiflexible cylinder. Brief descriptions are given of its use as a simple spring, a pressure-sensing device, or as a means of accommodating variations in pipework.

354.

Weil, N. A., and Newmark, N. M., "Large Plastic Deformations of Circular Membranes", J. Appl. Mech., 22, pp 533-538, 1955.

An investigation is presented for the plastic behavior of clamped circular membranes subjected to hydrostatic pressure, based on the Hencky-Mises theory. New strain-displacement relations, valid for finite deformations in the plastic domain, are introduced. The solution is presented in terms of two simultaneous implicit integral equations, which can be solved by numerical methods. The solution also permits the formulation of the instability condition. Experimental work consisted of bulge tests carried out on annealed copper plates of two thicknesses, whose τ-γ curve was previously determined from uniaxial tests. A good correlation was obtained between theoretical predictions and experimental results.

355.

Weingarten, V. I., Morgan, E. J., and Seide, P., "Elastic Stability of Thin-Walled Cylindrical and Conical Shells Under Axial Compression", AIAA J., 3 (3), pp 500-505, March 1965.

Results of an extensive experimental program on the stability of cylindrical and conical shells under axial compression are presented and discussed. The experimental data indicate that the buckling coefficient varies with radius-thickness ratio. A study of other data in the literature showed that most of the experimental results fell within or near the scatter-band obtained in the present evaluation. A lower bound design curve is also contained in the paper.

356.

Weismantel, E. E., Cole, C. F., and Bitler, J. A., "Welding Practices for Berylium Copper Alloys", Welding J., 42, pp 207-212, March 1963.

This paper provides an introduction to the use of beryllium-containing copper alloys in welded structures. The factors most affecting weldability and weldment properties of alloys containing 0.25 to 2.0 percent beryllium are: the refractory oxide formed during welding, weld fluidity, base metal conductivity, specific heat and post-welding heat treatment. Because of the refractory nature of beryllium oxide, the quality of welds resulting from multipass operations is influenced partially by the interpass joint preparation and cleaning procedures. In this aspect, the welding of these alloys requires practices similar to those followed in the welding of materials containing aluminum and titanium as hardening additions. Because the thermal conductivity and the melting point decrease with increases in beryllium content, the alloys containing more beryllium appear the more readily weldable. Weldment quality and mechanical properties before and after various thermal treatments for several beryllium copper alloys in sheet and plate form are discussed. Where good protective atmosphere is provided, an alloy similar to the base metal can be used as a filler metal. Using the gas tungsten- and metal-arc welding processes and the electron-beam process, little alloying occurs. After postweld thermal treatment, weld metal properties approach those of the base metal.

357.

Wells, J. D., "Development Tests - Aluminum Bellows", Stainless Steel Products Inc. Rept. No. 2115, November 7, 1963.

The purpose of this report is to describe the development tests performed on three aluminum bellows designs for the Martin Company. The assemblies tested include a 1.5-inch diameter bellows, a 6-inch diameter bellows and duct assembly, and a 10-inch diameter bellows. A further purpose of this report is to outline the difficulties encountered in vibration testing and to show that vibration dampers will be required on these designs.

358.

Werner, F. D., "The Design of Diaphragms for Pressure Gages Which use the Bonded Wire Resistance-Strain Gage", Proc. Soc. Exp. Stress Anal., 11 (1), pp 137-146, 1953.

The problem of compromising among high sensitivity, high natural frequency, small size, adequate strength, wide pressure range, linear response, etc., in the design of diaphragms for diaphragm type pressure gages which use the bonded wire resistance strain gage is examined in detail. A systematic procedure for finding the best compromise is worked out. A good basis for comparison among various materials is established, and a comparison is given in tabular form. The design procedure is given in 5 equations, and for steel, dural, and magnesium alloy, the design equations are graphed in a manner which makes design especially convenient and rapid. Some suggestions for making the diaphragm are included.

359.

Westerheide, D. E., Clifford, J. C., and Burnet, G., "A Diaphragm Pump for Liquid Metal Service", Ames Lab., Iowa State Univ. of Sci. & Tech., R&D Rept. No. N-63-11812.

The use of centrifugal and electromagnetic pumps for liquid metals is briefly reviewed. Details are provided on the construction and operation of a two-stage diaphragm pump successfully used for the first time in liquid metal service. From the results of a 5376-hour test of the pump it was concluded that it is well suited to the pumping of liquid metals at low flow rates where pulsating flow can be tolerated. Operating temperatures and pressures are limited only by the availability of suitable materials of construction.

360.

"When Selecting Bellows", Prod. Eng., pp 134-136, April 1936.

Descriptions are given of steps in the manufacture of gas-tight flexible metal bellows of corrosion-resistant materials formed from drawn tubes by hydraulic pressure. Methods of designing for minimum cost require consideration of bellows manufacturing processes.

361.
White, E. L., and Fink, F. W., "Materials of Construction for Handling Fluorine", Proc. of the Propellant Thermodyn. and Handling Conf., pp 161-181, 1959.

There is considerable information on the corrosion behavior of materials exposed to fluorine. No material is completely inert to attack by this extremely active element. However, many of the common construction materials, when used in the established temperature ranges, can be expected to give acceptable service. Nickel alloys can be used up to 1200 F; aluminum and magnesium to 900 F; copper, and possibly thorium, to 700 F; pure iron to 600 F; mild steels with low silicon content to 400 F; and titanium and zirconium to 300 F. Chromium plate is useful to at least 400 F and nickel plate to higher temperatures. The use of tantalum, tin, silver, lead, platinum is possible at room temperatures. Silicon, vanadium, rhenium, and uranium are attacked even below room temperature. Liquid fluorine at liquid-nitrogen temperatures is more corrosive than the gas at room temperature. The metals which can be used with liquid fluorine are nickel and nickel alloys, stainless steels, aluminum, magnesium, mild steel, titanium, tantalum, and zirconium. Except for very special applications, the only organic materials which can be used with either liquid or gaseous fluorine are the fluorocarbons. Polytetrafluoroethylene is the best. Of the nonmetallic inorganic materials, alumina is very resistant. Glass, asbestos, and some cermets may have limited uses, and carbon materials are not recommended for elevated temperatures.

362.
Whitten, D. C., "Ten Ways to Use Metal Diaphragms and Capsules", Prod. Eng., 29 (7), pp 92-93, February 17, 1958.

Brief descriptions are given of various applications for metal diaphragms.

363.
Wigotsky, V. W., "Volume Compensating Welded Bellows", Design News, 15 (10), pp 6-9, May 9, 1960.

Devices such as gyros, accelerometers, and other floated instruments are hermetically sealed, must correct for fluid-volume changes with temperature and often require optimum damping characteristics. This article presents typical applications, physical properties, and design data relative to use of volume-compensating welded bellows to achieve these objectives.

364.
Wigotsky, V. W., "Welded Diaphragm Bellows - Part I", Design News, 16 (3), pp 8-9, January 1961.

The versatility of welded diaphragm metal bellows has created many new uses and improved performance in many conventional applications. Welded bellows as a torque transmitting device on a submarine periscope and as a replacement for a spring in a fluid filled control mechanism are only two examples. They illustrate how the performance of these bellows can be varied to suit the need.

365.

Wigotsky, V. W., "Welded Diaphragm Bellows - Part II", Design News, 16 (5), pp 8-9, February 1961.

Design curves and charts were prepared from test data and mathematical analysis and are based upon AM 350 (AMS 5548), a precipitation-hardening stainless steel, heat-treated to Rc 42-45 hardness. Curves on spring rate are approximate and serve to orient the designer rather than pinpoint exact values. Curves on the life expectancy are conservative. The flat plate and nesting ripple contours generally are used in the zero to 300 psi pressure range and require a similar design approach. The single sweep and torus designs generally are used above 300 psi and require considerably different treatment. It appears desirable, therefore, to present comparable engineering data on these two contours at a later date.

366.

Wildhack, W. A., and Goerke, V. H., "Corrugated Metal Diaphragms for Aircraft Pressure-Measuring Instruments", NACA Tech. Note No. 738, 1939.

A large number of corrugated diaphragms of beryllium copper, phosphor bronze, and Z-nickel, having geometrically similar outlines but of various diameters and thicknesses, were formed by hydraulic pressing. The apparatus and the technique used in the manufacture, the testing, and the heat treatment are described. The shape of the diaphragms was such that the central deflections were nearly proportional to the differential pressures up to deflections of 2 percent of the diameter. The pressure-deflection characteristics of the various diaphragms were correlated with the thickness, the diameter, and the elastic properties by dimensional analysis to obtain formulas and charts applicable to the design of similar diaphragms. For comparison, some data are presented for flat diaphragms and for corrugated diaphragms differing slightly from the standard design. The use of the experimental results in the selection or the design of corrugated diaphragms is briefly discussed.

367.

Wildhack, W. A., et al., "Investigations of the Properties of Corrugated Diaphragms", ASME Trans., 79 (1), pp 65-82, January 1957.

The pressure-deflection characteristics of corrugated diaphragms are correlated by methods of dimensional analysis. Experimental results for various sizes, materials, thicknesses, and shapes of diaphragms indicate that the performance for diaphragms of any given shape may be computed from a dimensionless formula derived from experimental data on other diaphragms of that shape. Linear-shell equations are derived for combined bending and stretching effects with lateral loading terms for rotationally symmetrical shells in appropriate independent and dependent variations suitable for complicated meridial shapes, and with boundary conditions associated with practical diaphragm applications. The method used for solving this system of equations on an electronic digital computer is described and numerical solutions are presented for a specific diaphragm subjected to uniform pressure loading. Suggestions are presented for future research, both theoretical and experimental, on diaphragm properties and performance.

368.

Wildhack, W. A., and Goerke, V. H., "The Limiting Useful Deflections of Corrugated Metal Diaphragms", NACA Tech. Note No. 876, 1942.

The limiting useful deflection of a diaphragm may be defined as that deflection which is followed by an arbitrarily chosen allowable limit of hysteresis, aftereffect, drift, or zero shift. Preliminary results reported previously indicated that the limiting deflection is mainly dependent on the diameter, and the material and only slightly dependent on the thickness of the diaphragm. In order to investigate further the useful limits of diaphragm performance, measurements were made on a large number of corrugated diaphragms of similar shapes but of various sizes and various metals. The materials studied include phosphor bronze, beryllium copper, A-nickel, B-Monel, K-Monel, and Inconel. The apparatus used in making the measurements is described. Data were obtained on the relations between pressure and deflection, deflection and hysteresis, time and drift under constant load, time and recovery after release of load, and zero shift and deflection for the various diaphragms. Many of the results are presented graphically. The performances of the different materials are compared and the characteristic constants for each material are deduced for use with design formulas. The results are analyzed to determine the correlation of the limiting deflections with the thicknesses and diameters of the diaphragms and the elastic properties of the materials used.

369.

Williams, G. R., "Measuring Young's Modulus by the Resonance Method", Instr. Practice, 19, pp 319-321, April 1965.

The fundamental relationship between Young's Modulus and the velocity of sound is considered, and a new instrument is described which uses this relationship as a means of measurement.

370.

Winborne, R. A., "Simplified Formulas and Curves for Bellows Analysis", Atomics International, August 1, 1964.

Design of reliable bellows requires (1) solution of the problem, to obtain the required nominal dimensions by use of the best theoretical methods available, and (2) elimination of stress-raising influences which can produce stresses much higher than those calculated. Simplified theoretical design procedures, beam-theory equations with charts to supply curvature corrections, are presented in this report for welded plate, convolute, and toroidal bellows. Factors in design which, in large convolute-shaped bellows, produce stresses much higher than those calculated, are discussed in detail in another report. A digital-computer program was developed, based on asymptotic shell theory, to obtain design charts correlating stresses in shallow shell-shaped (welded plate) bellows with those in more simple structural elements. These design charts were developed to permit a presentation of four shell-theory parameters on one graph sheet, and thus avoid use of complicated nomographic charts.

371.

Winborne, R. A., "Stress and Elevated Temperature Fatigue Characteristics of Large Bellows", Atomics International, September 15, 1964 (N64-29352).

Ten large 20-in.-diameter 304 stainless steel bellows were tested to or near fatigue failure; nine to 1200 F sodium, and one in air at 70 F. The data indicated that, at 1200 F, fatigue life of axially deflected large convolute-shaped bellows, without internal pressure influence, was mainly determined by bellows geometry, and was associated with a factor μ, used frequently in asymptotic shell theory of convolute-shaped bellows. On a log-log chart there appeared to be a linear relationship between $1/\mu$ and cycles to failure of axially deflected, large convolute-shaped bellows at 1200 F. The fatigue life of a bellows with a high μ value ($\mu = 6$) was less than $1/100$ that of a bellows with a low μ value ($\mu = 0.25$). Conventional high μ ($\mu > 2$) bellows always failed at, or near, the welded junctures of the bellows-to-pipe ends where stresses were highest. With stresses very uniformly distributed over their profiles, low μ ($\mu = 0.25$) bellows appeared to be relatively insensitive to stress raising influences. The fatigue test performance of one toroid-shaped bellows was excellent. Charts in this report show axial stress distribution over exterior bellows surfaces induced by bellows axial deflection, and by internal pressurization. The influence of root rings on stress distribution is presented graphically.

372.

Wintergerst, E., and Lintz, H., "Properties and Applications of Metal Diaphragms", Regelungstechnische Praxis (Munich), $\underline{1}$ (5), pp 160-165, May 1959 (in German).

Introductory remarks are followed by a survey of the method of calculation and also of the properties and applications of metal diaphragms. A short reference is made to the wellknown formulas for calculating plain metal diaphragms. However, the methods of approximate calculation of concentrically convoluted diaphragms, which have been developed only recently, are dealt with more fully. The article contains, furthermore, a brief report on empirically found values and examples of the application of metal diaphragms in measuring and control devices, with particular consideration of the margin of safety at excess pressures.

373.

Wolley, H.W.G., "Manufacture of Barometric Bellows and Like Corrugated Tubes", Nuclear Eng., $\underline{2}$, p 494, November 1957 (British Patent 777,146).

The main object of this invention is to form a corrugated tube or metal bellows in which the wall thickness is substantially constant in the corrugated parts, that is, within a tolerance of ± 0.001 inch with a wall thickness of the order of 0.020 inch. According to the invention a process for forming a tube of uniform wall thickness into a corrugated tube of uniform wall thickness in the corrugated parts comprises forming the corrugations successively with the unformed part of the tube unrestrained from moving axially toward the corrugations as they are formed.

374.

Wrathall, T., "Miniature Pressure Cells", Instruments, 26, pp 736-739, May 1953.

High-speed aerodynamic testing requires the use of small pressure cells having good dynamic characteristics. Such cells usually employ a fixed-edge diaphragm and make use of sensitive electronic detecting equipment. Construction details and general characteristics are given for three types of miniature pressure cells developed and used by the NACA. These three are resistive, capacitive, and inductive. Buffeting and flutter research requires the measurement of fluctuating air loads so that with increased emphasis on this kind of testing such cells will play an increasingly important role as a research tool.

375.

Zakharov, Yu. G., "Measuring Pulsating Pressures With the Aid of Membrane Transducers", AFSC, WPAFB, FTD-TT-63-737, AD 433076 (translation).

In the investigation of transient regimes and in a number of other aerodynamic problems it becomes necessary to measure a pressure which changes with time. The instruments usually used for this kind of measurement are membrane transducers, which transform a variable pressure into an electrical voltage or current, the changes in which can easily be recorded with the aid of an oscillograph. The different kinds of electrical transducers - capacitive, inductance, tensometric - are widely used at the present time in aerometry. This article attempts to determine experimentally the correction factors for the measured amplitude and phase of a pulsating pressure, considering the transducer and the inlet tube as a single oscillating system.

376.

Zenova, E. F., and Novozhilov, V. V., "Symmetric Deformation of a Toroidal Shell", Prikl. Mat. Mekh., 85 (5), pp 521-530, 1951 (in Russian).

This paper gives the asymptotic solution for the homogeneous problem for the toroidal shell in terms of Hankel functions. The particular solution is developed in terms of a trigonometric series.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43212	Unclassified
	2b. GROUP

3. REPORT TITLE

STATE-OF-THE-ART SURVEY OF METALLIC BELLOWS AND DIAPHRAGMS FOR AEROSPACE APPLICATIONS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Period covered - March 1 to July 31, 1965.
Interim report on the state of the art under USAF Contract No. 04(611)-10532.

5. AUTHOR(S) *(Last name, first name, initial)*

Hulbert, L. E., Keith, R. E., and Trainer, T. M.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1965	171	46 + 376 in Annotated Biblio.

8a. CONTRACT OR GRANT NO. AF 04(611)-10532	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. AFS No. 750 G AFSC Project No. 6753 c. AFSC Task No. 675304	
	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFRPL-TR-65-215
d.	

10. AVAILABILITY/LIMITATION NOTICES

Qualified requestors may obtain copies of this report from the Defense
Documentation Center

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Rocket Propulsion Laboratory Research and Technology Division Air Force Systems Command

13. ABSTRACT

A 2-1/2-year program has been under taken to establish analytical
procedures, stress analysis methods, techniques for manufacturing control,
and other factors essential to the successful design and fabrication of
metallic bellows and diaphragms. The initial phase of the program has in-
cluded a state-of-the-art survey to assist in the determination of the best
means of accomplishing the over-all program objectives. This report sum-
marizes the results of the survey and presents recommendations for the
remainder of the program. An annotated bibliography of 376 references is
included.

DD FORM 1473
1 JAN 64

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Accumulators						
Adams-Bashford						
Adams-Moulton						
Aneroid Capsules						
Axisymmetric Shells						
Bellows						
Bellows Analysis						
Bellows Configuration						
Bellows Design						
Bellows Evaluation						
Bellows Manufacturing						
Computer Solutions						
Diaphragms						
Diaphragm Analysis						
Diaphragm Configuration						
Diaphragm Design						
Diaphragm Evaluation						
Diaphragm Manufacturing						
Direct Integration						
Elastic Analysis						
End-Face Seals						
Expansion Joints						
Finite Difference						
Flexible Connectors						
Hermetic Seals						
Hydraulic Actuators						
Hydraulic Motors						
Linear-Shell Analysis						
Metal Hose						
Metallic Bellows						
Metallic Diaphragms						
Motion Transducers						
Nonlinear-Shell Analysis						

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Runge-Kutta						
Shaft Seals						
Shells of Revolution						
Shock Absorbers						
Temperature Sensors						
Vibration Dampeners						
Volume Compensators						